

# Optimizing DF Cognitive Radio Networks with Full-Duplex-Enabled Energy Access Points

Hong Xing, Xin Kang, Kai-Kit Wong, and Arumugam Nallanathan

## Abstract

With the recent advances in radio frequency (RF) energy harvesting (EH) technologies, wireless powered cooperative cognitive radio network (CCRN) has drawn an upsurge of interest for improving the spectrum utilization with incentive to motivate joint information and energy cooperation between the primary and secondary systems. Dedicated energy beamforming (EB) is aimed for remedying the low efficiency of wireless power transfer (WPT), which nevertheless arouses out-of-band EH phases and thus low cooperation efficiency. To address this issue, in this paper, we consider a novel RF EH CCRN aided by full-duplex (FD)-enabled energy access points (EAPs) that can cooperate to wireless charge the ST while concurrently receiving PT's signal in the first transmission phase, and to perform decode-and-forward (DF) relaying in the second transmission phase. We investigate a weighted sum-rate maximization problem subject to the transmitting power constraints as well as a total cost constraint using successive convex approximation (SCA) techniques. A zero-forcing (ZF) based suboptimal scheme that is locally optimal at the EAPs is also derived. Various tradeoffs between the weighted sum-rate and other system parameters are provided in numerical results to corroborate the effectiveness of the proposed solutions against the benchmark schemes.

## Index Terms

cognitive radio, cooperative communication, full-duplex, decode-and-forward, D.C. programming, successive convex approximation, power splitting, energy harvesting.

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## I. INTRODUCTION

With the rapid development of wireless services and applications, the demand for frequency resources has dramatically increased. How to accommodate these new wireless services and applications within the limited radio spectrum becomes a big challenge facing the modern society [1]. The compelling need to establish more flexible spectrum regulations motivates the advent of cognitive radio (CR) [2]. Cooperative cognitive radio networks (CCRN) further pave way to improve the spectrum efficiency of a CR system by advocating cooperation between the primary and secondary systems for mutual benefits. Compared with classical CR approaches [3], CCRN enables cooperative gains on top of CR in the sense that the secondary transmitter (ST) helps to provide the diversity and enhance the performance of primary transmission via relaying the primary user (PU)'s message while being allowed to access the PU's spectrum.

Although the conventional CCRN benefits from information-level cooperation, its implementation in real world might be limited due to STs' power constraints, especially when the STs are low-power devices, such as energy constrained wireless sensors and small cell relays. With the advent of various energy harvesting (EH) technologies, CCRN has now been envisioned to improve the overall system spectrum efficiency by enabling both information-level and energy-level cooperation [4]. Except for the well-known energy sources such as solar and wind, ambient radio signal has recently been exploited as a new viable source for wireless EH (WEH) (see [5] and references therein). Joint information and energy cooperation in CR networks has therefore been actively investigated in many interesting scenarios, e.g., [6–9].

The benefit of radio frequency (RF)-powered CCRN is nevertheless compromised by the low wireless power transfer (WPT) efficiency mainly due to the severe RF signal attenuation over distance. One way to improve the WPT efficiency is to employ multiple antennas at the ST, which can improve the EH efficiency of the secondary system [7]. The other way to boost the WPT efficiency is to power the ST via WPT from the dedicated energy/hybrid access point (EAP/HAP) [8] in addition to the PU. However, the above works all assume that the involved devices operate in half-duplex (HD) mode, which provides more reliable power supplies for CCRN at the expense of some spectrum efficiency. In continuous effort to address this issue, full-duplex (FD)-enabled communications with wireless information and power transfer has sparked an upsurge of interest thanks to the advance in antenna technologies (see [10–14] and references therein).

In this paper, we consider a spectrum-sharing decode-and-forward (DF) relaying CR network consisting of one pair of primary transmitter (PT) and primary receiver (PR), and one pair of

multiple-input multiple-output (MIMO) secondary users (SUs). A number of multi-antenna FD EAPs are coordinated to transfer wireless power to the ST while simultaneously listening to information sent from the PT in the first transmission phase, and decode then forward the PT's message to the PR in HD mode in the second transmission phase. The ST is required to assist the primary transmission and earn the rights to access the PU's spectrum in return; the EAPs are paid by the system as an incentive to support the cooperative WPT and wireless information transfer (WIT). We assume that there is no direct link between the PT and the PR due to severe pathloss [13], and the global channel state information (CSI) is available at the centralized coordination point. The main contributions of this paper are summarized as follows.

- The weighted sum-rate of the FD EAPs-aided CCRN system is maximized using successive convex approximation (SCA) techniques subject to the per-EAP power constraint for WPT and WIT, respectively, the ST's transmitting power constraint, and a practical cost budget including the payment made to the EAPs for their dedicated WPT and WIT.
- The centralized optimization enables cooperation among the EAPs to effectively mitigate the interference caused by the energy signals with ST's information decoding (ID), and the self-interference (SI) that degrades EAPs' reception of the PT's signal.
- A low-complexity suboptimal design locally nulling out the SI at the EAPs is also developed in order to reduce the computational cost of the iterative algorithm, and is validated by computer simulations that near-optimal performance can be achieved.
- Various tradeoffs, e.g., priority between primary and secondary transmissions, energy and cost allocations between WPT and WIT, are studied by solving the optimization problems, and evaluated by simulations to provide useful insights for system design in practice.

In [13], an FD-enabled CCRN was studied, where the residual SI associated with the cognitive base station (CBS) operating in FD mode was modelled by its imperfect transmission as an amplify-and-forward (AF) or DF relay. Instead of an ST serving as CBS with sufficient power supply, our work considers an energy-starving ST completely relying on being wirelessly charged by the EAPs and the ST, which necessitates interference management caused by the WPT. In [7], the multi-antenna ST receives information from the primary transmitter (PT) and is also fed with energy by the PT using PS and/or time switching (TS) receiver, which enlarges the achievable primary-secondary rate region. The improved RF EH capability and cooperative gains the ST is seen though, the energy received by the ST is not intended for WPT and thus the increase in the achievable rate of the secondary system is limited. In contrast, the deployment

of cooperative FD-enabled EAPs intended for WPT breaks this bottleneck. For this reason, a wireless powered communication network (WPCN) with a FD HAP and a set of WEH-enabled users was investigated in [14], where the HAP implements FD through two specialized antennas: one for broadcasting wireless energy in the downlink (DL) and the other for simultaneously receiving information from the time division multiple access (TDMA) users in the uplink (UL). It is worth noting that perfect SI cancellation (SIC) between the transmitting and receiving antennas of the HAP was assumed in [14], which is nevertheless not achievable and unrealistic in practice even with the state-of-the-art FD techniques [15]. A similar set-up was considered in [16], whereas our work differs from it mainly in the following aspects:

- First of all, the considered EAPs in this paper are FD empowered so that this fundamentally improves the spectral efficiency of the CCRN system.
- Second, compared with the non-cooperative EAPs whose power levels vary discretely, we fully exploit the EAPs by enabling their cooperation in both the WPT and WIT phases via continuous power control, which is an extension to the non-cooperative model.

The remainder of the paper is organized as follows: Section II and III introduces the system model of the CCRN assisted by FD-enabled EAPs, and formulates the weighted sum-rate maximization problem, respectively. Section IV investigates the feasibility of a tractable reformulation of the original problem; proposes an SCA-based iterative solution along with a suboptimal scheme based upon zero-forcing (ZF) the SI. Benchmark schemes are studied in Section V. Section VI provides numerical results to compare the performance achieved by different schemes. Finally, Section VII concludes the paper.

*Notation*—We use the upper case boldface letters for matrices and lower case boldface letters for vectors.  $(\cdot)^T$ ,  $(\cdot)^H$ , and  $\text{Tr}(\cdot)$  denote the transpose, conjugate transpose, and trace operations on matrices, respectively.  $\|\cdot\|_p$  is  $\ell^p$ -norm of a vector with  $p = 2$  by default. The Kronecker product of two matrices is denoted by  $\otimes$ .  $\mathbf{A} \succeq 0$  indicates that  $\mathbf{A}$  is a positive semidefinite (PSD) matrix, and  $\mathbf{I}$  denotes an identity matrix with appropriate size.  $\mathbb{E}[\cdot]$  stands for the statistical expectation of a random variable (RV). In addition,  $\mathbb{C}(\mathbb{R})^{x \times y}$  stands for the field of complex (real) matrices with dimension  $x \times y$ , and  $\mathbb{Z}$  is the set of integer.  $(\cdot)^*$  means the optimum solution.

## II. SYSTEM MODEL

In this paper, we consider a WEH-enabled CCRN that consists of one primary transmitter-receiver pair, one secondary transmitter-receiver pair, and a set of FD EAPs denoted by  $\mathcal{K} =$

$\{1, \dots, K\}$ . The primary transmitter and receiver are denoted by PT and PR, respectively, while the secondary transmitter and receiver are denoted by ST and SR, respectively. The PT and the PR are equipped with one antenna each, while the ST and the SR are equipped with  $N$  and  $M$  antennas, respectively. The number of transmitting and receiving antennas at the  $k$ th EAP are denoted by  $N_{T,k}$  and  $N_{R,k}$ , respectively,  $\forall k \in \mathcal{K}$ , and  $N_k = N_{T,k} + N_{R,k}$ . We assume that the ST is batteryless, and thus it resorts to WEH as its only source of power for information transmission.

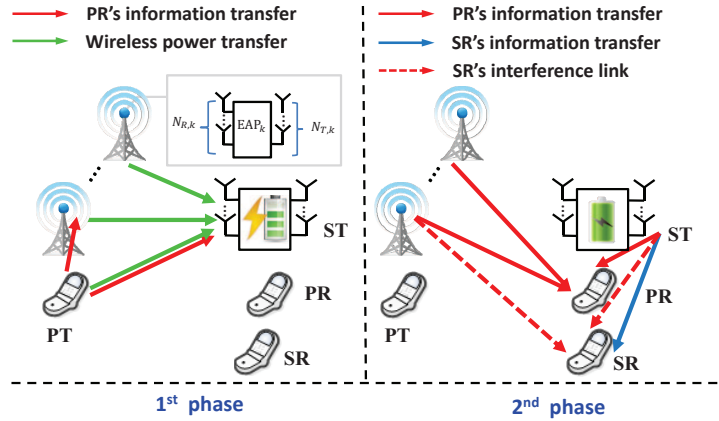


Fig. 1. Transmission protocol for a wireless powered CCRN.

As illustrated by Fig. 1, a two-slot (with equal length) transmission protocol is assumed to be adopted. In the first time slot, the PT transfers the energy-bearing primary user's signal to the ST. Concurrently, the EAPs operating in FD mode cooperate to transfer wireless power to the ST using  $N_{T,k}$ 's antennas, while jointly receiving information from the PT using  $N_{R,k}$ 's antennas. In the secondary time slot, the ST decodes and forwards PT's message and superimposes it on its own to broadcast to the PR and the SR. Meanwhile, the decoded PT's information is also forwarded to the PR by the EAPs that employ all of its  $N_k$  antennas for information transmission. Let  $s$  denote PT's transmitting signal that follows the circularly symmetric complex Gaussian (CSCG) distribution, denoted by  $s \sim \mathcal{CN}(0, 1)$ , and  $\mathbf{x} \sim \mathcal{CN}(\mathbf{0}, \mathbf{X})$ ,  $\mathbf{x} \in \mathbb{C}^{\sum_{k \in \mathcal{K}} N_{T,k} \times 1}$ , the energy signals coordinately transmitted by  $K$  EAPs, where  $\mathbf{X}$  is the covariance matrix of  $\mathbf{x}$ . On the other hand,  $\mathbf{x}$  can also be alternatively expressed by  $\mathbf{x} = [\mathbf{x}_k]_{k=1}^K$ , where  $\mathbf{x}_k \in \mathbb{C}^{N_{T,k} \times 1}$  is the energy signal transmitted by each individual EAP, and is subject to per-EAP power constraint given by  $\mathbb{E}[\|\mathbf{x}_k\|^2] \leq P_0$ ,  $\forall k \in \mathcal{K}$ .

### A. The First Time Slot

**Received signal at the ST.** In this paper, we assume that the ST employs a dynamic power splitting (DPS) receiver [17] for EH and information decoding (ID) from the same stream of received signal, where  $\varrho$  portion of the received signal power is used to feed the energy supply while the remaining  $1 - \varrho$  for ID. As a result, the signal received by the ST is given by

$$\mathbf{y}_{ST}^{(1)} = \sqrt{1 - \varrho}(\mathbf{h}_{p,ST}\sqrt{P_p}s + \mathbf{H}_{EAP,ST}\mathbf{x} + \mathbf{n}_a) + \mathbf{n}_c, \quad (1)$$

where  $\mathbf{h}_{p,ST} \in \mathbb{C}^{N \times 1}$  denotes the complex channel from the PT to the ST;  $\mathbf{n}_a$  denotes the additive white Gaussian noise (AWGN) at the antennas in RF-band with zero mean and variance  $\sigma_{n_a}^2$ ;  $\mathbf{n}_c$  is the RF-band to baseband signal conversion noise denoted by  $\mathbf{n}_c \sim \mathcal{CN}(\mathbf{0}, \sigma_{n_c}^2 \mathbf{I})$ . Furthermore, assuming that the linear receiving beamforming performed by the ST is  $\mathbf{u}_1^H \mathbf{y}_{ST}^{(1)}$ , where  $\mathbf{u}_1 \in \mathbb{C}^{N \times 1}$  is given by maximizing ST's signal-to-interference-plus-noise ratio (SINR) as follows.

$$\mathbf{u}_1^* = \arg \max_{\mathbf{u}_1} \frac{(1 - \varrho)P_p |\mathbf{u}_1^H \mathbf{h}_{p,ST}|^2}{\mathbf{u}_1^H ((1 - \varrho)(\mathbf{H}_{EAP,ST} \mathbf{X} \mathbf{H}_{EAP,ST}^H + \sigma_{n_a}^2 \mathbf{I}) + \sigma_{n_c}^2 \mathbf{I}) \mathbf{u}_1}, \quad (2)$$

which proves to be the eigenvector corresponding to the largest (generalized) eigenvalue of matrices  $((1 - \varrho)(\mathbf{H}_{EAP,ST} \mathbf{X} \mathbf{H}_{EAP,ST}^H + \sigma_{n_a}^2 \mathbf{I}) + \sigma_{n_c}^2 \mathbf{I}, \mathbf{h}_{p,ST} \mathbf{h}_{p,ST}^H)$ . It thus leads to the SINR at the ST in the first transmission phase given by

$$\begin{aligned} \lambda_{\max}((1 - \varrho)P_p \mathbf{A}^{-\frac{1}{2}} \mathbf{h}_{p,ST} \mathbf{h}_{p,ST}^H \mathbf{A}^{-\frac{1}{2}}) &\stackrel{(a)}{=} \lambda_{\max}((1 - \varrho)P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1} \mathbf{h}_{p,ST}) \\ &= (1 - \varrho)P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1} \mathbf{h}_{p,ST}, \end{aligned} \quad (3)$$

where  $\mathbf{A} = (1 - \varrho)(\mathbf{H}_{EAP,ST} \mathbf{X} \mathbf{H}_{EAP,ST}^H + \sigma_{n_a}^2 \mathbf{I}) + \sigma_{n_c}^2 \mathbf{I}$ , and (a) is due to the rank-one  $\mathbf{A}^{-\frac{1}{2}} \mathbf{h}_{p,ST} \mathbf{h}_{p,ST}^H \mathbf{A}^{-\frac{1}{2}}$ .

**Received signal at the EAPs.** The received PT's signal at the receiving antennas of EAPs that is interfered with the energy signals transmitted by the same EAPs can be expressed in a vector form given by

$$\mathbf{y}_{EAP} = \mathbf{h}_{p,EAP} \sqrt{P_p} s + \mathbf{H}_{TR} \mathbf{x} + \mathbf{n}_{EAP}^{(1)}, \quad (4)$$

where  $\mathbf{h}_{p,EAP} = [\mathbf{h}_{p,EAP_1}^H, \dots, \mathbf{h}_{p,EAP_K}^H]^H$  with  $\mathbf{h}_{p,EAP_k} \in \mathbb{C}^{N_{R,k} \times 1}$ ,  $k \in \mathcal{K}$ , denoting the complex channel from the PT to the  $k$ th EAP;  $\mathbf{H}_{TR}$  indicates the effective loop interference (LI) channel from the transmitting to the the receiving antennas of the EAPs after analogue domain SIC, in which the block matrices  $\mathbf{H}_{T_k, R_k} \in \mathbb{C}^{N_{R,k} \times N_{T,k}}$  on the diagonal of  $\mathbf{H}_{TR}$ ,  $\forall k$ , denote the intra-EAP LI channels from within the  $k$ th EAP, and the matrices  $\mathbf{H}_{T_i, R_j}$  off the diagonal,  $\forall i \neq j$ ,

represent the inter-EAP LI channels from the  $i$ th EAP to the  $j$ th EAP;  $\mathbf{n}_{EAP}^{(1)}$  is assumed to be the AWGN noise received at the EAPs, i.e.,  $\mathbf{n}_{EAP}^{(1)} \sim \mathcal{CN}(\mathbf{0}, \sigma_{EAP}^2 \mathbf{I})$ . Without loss of generality (w.l.o.g.),  $\mathbf{H}_{TR}$  is given by  $\mathbf{H}_{TR} = \sqrt{\varphi^2} \bar{\mathbf{H}}_{TR}$ , where each element in  $\mathbf{H}_{T_k, R_k}$ 's is a complex Gaussian RV with zero mean and variance of  $\varphi^2$ ; each element in  $\mathbf{H}_{T_i, R_j}$ 's is a complex Gaussian RV with zero mean and variance of  $\varphi^2$  multiplied by path-loss.  $\bar{\mathbf{H}}_{TR}$  denotes the normalized complex LI channel, and  $\varphi^2 \in [0, 1]$  indicates the residual LI channel gains.

It is worth noting that the analogue domain SIC is implemented though, the power level of the residual LI can still be much larger than that of the desired signal [18], i.e.,  $\varphi^2 \mathbb{E}[\|\bar{\mathbf{H}}_{TR} \mathbf{x}\|^2] \gg P_p \|\mathbf{h}_{p, EAP}\|^2$ , due to which the following concern arises. Channel estimation errors w.r.t the block diagonal matrices  $\bar{\mathbf{H}}_{T_k, R_k}$ 's cannot be neglected in general. Assume that the estimation of  $\bar{\mathbf{H}}_{TR}$  is given by  $\bar{\mathbf{H}}_{TR} = \hat{\mathbf{H}}_{TR} + \sqrt{\varepsilon^2} \tilde{\mathbf{H}}_{TR}$  [10], where  $\hat{\mathbf{H}}_{TR}$  denotes the estimation of  $\bar{\mathbf{H}}_{TR}$ ;  $\tilde{\mathbf{H}}_{TR}$  denotes its error channel, whose elements are all complex Gaussian RVs with zero mean and variance of 1 in the block matrices  $\tilde{\mathbf{H}}_{T_k, R_k}$ 's, and variance of path-loss in the block matrices  $\mathbf{H}_{T_i, R_j}$ 's, respectively.  $\varepsilon^2 \ll 1$  denotes the level of estimation accuracy. Hence, after analogue-to-digital conversion (ADC) [19], digital domain SIC is further applied to subtract  $\sqrt{\varphi^2} \hat{\mathbf{H}}_{TR}$  from (4). The processed signal can be finally expressed as

$$\bar{\mathbf{y}}_{EAP} = \mathbf{h}_{p, EAP} \sqrt{P_p} s + \sqrt{\varphi^2 \varepsilon^2} \tilde{\mathbf{H}}_{TR} \mathbf{x} + \mathbf{n}_{EAP}^{(1)}. \quad (5)$$

For the purpose of exposition, we denote  $\varphi \varepsilon$  by  $\theta$  in the sequel.

Furthermore, since the  $K$  EAPs are coordinated, they can perform joint decoding of the PT's signal  $s$  to maximize their receiving SINR. Therefore the optimum receiving beamforming  $\mathbf{u}_2$  is designed such that

$$\text{SINR}_{EAP} = \max_{\mathbf{u}_2} \frac{P_p |\mathbf{u}_2^H \mathbf{h}_{p, EAP}|^2}{\mathbf{u}_2^H (\theta^2 \tilde{\mathbf{H}}_{TR} \mathbf{X} \tilde{\mathbf{H}}_{TR}^H + \sigma_{EAP}^2 \mathbf{I}) \mathbf{u}_2}, \quad (6)$$

which is equal to  $P_p \mathbf{B}^{-\frac{1}{2}} \mathbf{h}_{p, EAP} \mathbf{h}_{p, EAP}^H \mathbf{B}^{-\frac{1}{2}}$  with  $\mathbf{B} = \theta^2 \tilde{\mathbf{H}}_{TR} \mathbf{X} \tilde{\mathbf{H}}_{TR}^H + \sigma_{EAP}^2 \mathbf{I}$ .

### B. The Second Time Slot

**Transmitted signal at the ST.** In the second time slot, the ST extracts the PR's desired message and superimposes it on its own message as follows.

$$\mathbf{x}_{ST}^{(2)} = \mathbf{w}_p s + \mathbf{q}_s, \quad (7)$$

where  $\mathbf{w}_p$  is the beamforming vector for  $s$ , while  $\mathbf{q}_s$  is the transmitted signal conveying the SR's information aimed for multiplexing MIMO transmission, the covariance matrix of which

is  $\mathbb{E}[\mathbf{q}_s \mathbf{q}_s^H] = \mathbf{Q}_s$ . As mentioned before, the transmitting power for the ST is solely supplied by its harvest power, i.e.,

$$\text{Tr}(\mathbf{Q}_s) + \|\mathbf{w}_p\|^2 \leq \eta \varrho P_{\text{EH}}(\mathbf{X}), \quad (8)$$

where  $P_{\text{EH}}(\mathbf{X}) = \text{Tr}(\mathbf{H}_{EAP,ST} \mathbf{X} \mathbf{H}_{EAP,ST}^H) + P_p \|\mathbf{h}_{p,ST}\|^2$  is the total wireless transferred power, and  $\eta$  denotes the EH conversion efficiency.

**Transmitted signal at the EAPs.** In the second time slot, the EAPs cooperatively transmit the decoded PT's message to the PR using all of their  $N_k$ 's antennas via beamforming  $\mathbf{v}_p s$ , where  $\mathbf{v}_p = [\mathbf{v}_{p,1}^H, \dots, \mathbf{v}_{p,K}^H]^H$ , and  $\mathbf{v}_{p,k} \in \mathbb{C}^{N_k \times 1}$ ,  $k \in \mathcal{K}$ , represents the  $k$ th EAP's beamforming vector.

**Received signal at the PR.** In the second time slot, PR receives the forwarded PT's message from both the ST and EAPs as follows.

$$y_{PR}^{(2)} = \mathbf{g}_{sp}^H \mathbf{x}_{ST}^{(2)} + \mathbf{g}_{EAP,p}^H \mathbf{v}_p s + n_{PR}^{(2)}, \quad (9)$$

where  $\mathbf{g}_{sp} \in \mathbb{C}^{N \times 1}$  is the Hermitian transpose of the complex channels from the ST to the PR,  $\mathbf{g}_{EAP,p} = [\mathbf{g}_{EAP_1,p}^H, \dots, \mathbf{g}_{EAP_K,p}^H]^H$  with  $\mathbf{g}_{EAP_k,p} \in \mathbb{C}^{N_k \times 1}$ ,  $k \in \mathcal{K}$ , is the Hermitian transpose of those from the EAPs to the PR, and  $n_{PR}^{(2)}$  is the AWGN at the PR denoted by  $n_{PR}^{(2)} \sim \mathcal{CN}(0, \sigma_{PR}^2)$ . Plugging (7) into (9),  $y_{PR}^{(2)}$  can be rewritten as

$$y_{PR}^{(2)} = (\mathbf{g}_{sp}^H \mathbf{w}_p + \mathbf{g}_{EAP,p}^H \mathbf{v}_p) s + \mathbf{g}_{sp}^H \mathbf{q}_s + n_{PR}^{(2)}. \quad (10)$$

The receiving SINR for the PR that treats the interference as noise in the second transmission slot is thus given by

$$\text{SINR}_{PR} = \frac{|\mathbf{g}_{sp}^H \mathbf{w}_p + \mathbf{g}_{EAP,p}^H \mathbf{v}_p|^2}{\mathbf{g}_{sp}^H \mathbf{Q}_s \mathbf{g}_{sp} + \sigma_{PR}^2}. \quad (11)$$

Accordingly, the achievable DF relaying rate for the PR, denoted by  $r_{PR}(\mathbf{X}, \varrho)$ , is given by

$$r_{PR}(\mathbf{X}, \varrho) = \min \left\{ \max \left\{ \frac{1}{2} \log_2 (1 + (1 - \varrho) P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\varrho, \mathbf{X}) \mathbf{h}_{p,ST}) \right\}, \frac{1}{2} \log_2 (1 + P_p \mathbf{h}_{p,EAP}^H \mathbf{B}^{-1}(\mathbf{X}) \mathbf{h}_{p,EAP}) \right\}, \frac{1}{2} \log_2 \left( 1 + \frac{|\mathbf{g}_{sp}^H \mathbf{w}_p + \mathbf{g}_{EAP,p}^H \mathbf{v}_p|^2}{\mathbf{g}_{sp}^H \mathbf{Q}_s \mathbf{g}_{sp} + \sigma_{PR}^2} \right) \right\}. \quad (12)$$

**Received signal at the SR.** The received signal at the SR is given by

$$\mathbf{y}_{SR}^{(2)} = \mathbf{G}_{ss} \mathbf{q}_s + (\mathbf{G}_{ss} \mathbf{w}_p + \mathbf{G}_{EAP,s} \mathbf{v}_p) s + \mathbf{n}_{SR}^{(2)}, \quad (13)$$



where  $\mathbf{G}_{ss}$  denotes the MIMO channels between the ST and the SR,  $\mathbf{G}_{EAP,s}$  represents the interference channels to the SR caused by the EAPs, and  $\mathbf{n}_{SR}^{(2)}$  is the received noise at the SR, denoted by  $\mathbf{n}_{SR}^{(2)} \sim \mathcal{CN}(0, \sigma_{SR}^2 \mathbf{I})$ . Assuming that dirty-paper coding and successive interference cancellation have been performed at the ST and the SR, respectively, the SR first decodes the PR's message, then subtracts it from the received signal by reconstruction, and finally recovers its own message. The achievable rate for the secondary system's overlaying MIMO transmission, denoted by  $r_{SR}$ , is given by

$$r_{SR}(\mathbf{Q}_s) = \frac{1}{2} \log_2 \det \left( \mathbf{I} + \frac{\mathbf{G}_{ss} \mathbf{Q}_s \mathbf{G}_{ss}^H}{\sigma_{SR}^2} \right). \quad (14)$$

### III. PROBLEM FORMULATION

In this paper, we assume that the spectrum sharing CCRN of interest aims to maximize the weighted sum-rate, i.e.,  $c_1 r_{PR}(\mathbf{X}, \varrho) + c_2 r_{SR}(\mathbf{Q}_s)$  (c.f. (12) and (14)), where  $c_1$  and  $c_2$  are weight coefficients that balance the priority of service between the primary and secondary system. In particular, we consider the cost for implementing wireless powered CCRN. As mentioned before, the ST is required to assist with the primary transmission by DF relaying using its harvested power from the EAPs and the PT. Therefore, the EAPs charge  $c_3 \eta \text{Tr}(\mathbf{H}_{EAP,ST} \mathbf{X} \mathbf{H}_{EAP,ST}^H)$  from the ST for its harvested power, where  $c_3$  is a cost conversion factor denoting the payment per unit of power. Moreover, the EAPs are assumed to be able to decode and forward PT's message for the purpose of diversifying the PT's information transmission and alleviating the burden of ST's limited EH capability. As a return, the system is required to pay the EAPs an amount of  $c_4 |\mathbf{g}_{EAP,p}^H \mathbf{v}_p|^2$  for their cooperative transmission, where  $c_4$  represents the cost per unit of received PT's signal power by the PR (c.f. (9)). In summary, the total cost for the FD EAPs-aiding CCRN is constrained by  $c_3 \eta \varrho \text{Tr}(\mathbf{H}_{EAP,ST} \mathbf{X} \mathbf{H}_{EAP,ST}^H) + c_4 |\mathbf{g}_{EAP,p}^H \mathbf{v}_p|^2 \leq C$ , where  $C$  is the budget of the ST. It is worth noting that this constraint will have a impact on the system only when  $C \leq C_{\max}$ , where  $C_{\max}$  denotes the largest possible cost given by

$$C_{\max} = c_3 \eta \varrho \text{Tr}(\mathbf{H}_{EAP,ST} \mathbf{X}^* \mathbf{H}_{EAP,ST}^H) + c_4 P_0 \|\tilde{\mathbf{g}}_{EAP,p}\|_1^2. \quad (15)$$

In (15),  $\mathbf{X}^*$  denotes the covariance of the coordinatedly transmitted energy beams that are able to transfer the maximum amount of power given by

$$\begin{aligned} \max_{\mathbf{X}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p} \quad & \text{Tr}(\mathbf{H}_{EAP,ST} \mathbf{X} \mathbf{H}_{EAP,ST}^H) \\ \text{s.t.} \quad & \text{Tr}(\mathbf{E}_k \mathbf{X}) \leq P_0, \forall k, \end{aligned}$$

and  $\tilde{\mathbf{g}}_{EAP,p} = [\|\mathbf{g}_{EAP,p,1}\|_2, \dots, \|\mathbf{g}_{EAP,p,K}\|_2]^T$  with  $\mathbf{g}_{EAP,p,k} \in \mathbb{C}^{N_k \times 1}$ 's given by  $\mathbf{g}_{EAP,p} = [\mathbf{g}_{EAP,p,1}^T, \dots, \mathbf{g}_{EAP,p,K}^T]^T$ . On the other hand, the maximum amount of PT's signal power received by the PR, i.e.,  $P_0 \|\tilde{\mathbf{g}}_{EAP,p}\|_1^2$ , is derived as follows.

$$|\mathbf{g}_{EAP,p}^H \mathbf{v}_p|^2 \stackrel{(a)}{\leq} \left( \sum_{k=1}^K |\mathbf{g}_{EAP,p,k}^H \mathbf{v}_{p,k}| \right)^2 \stackrel{(b)}{\leq} \left( \sqrt{P_0} \sum_{k=1}^K \|\mathbf{g}_{EAP,p,k}\|_2 \right)^2 = P_0 \|\tilde{\mathbf{g}}_{EAP,p}\|_1^2, \quad (16)$$

where the equality in (a) holds when all  $\mathbf{g}_{EAP,p,k}^H \mathbf{v}_{p,k}$ 's are aligned in the same direction ( $\angle 0^\circ$  herein), and (b) is achieved by Cauchy-Schwartz inequality.

Consequently, the weighted sum-rate maximization of the system, subject to the harvested power at the ST, the total cost charged by the EAPs, and the per-EAP power constraints for each EAP's WPT and WIT, respectively, can be readily formulated as follows.

$$(P1) : \max_{\mathbf{X}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p, \varrho} c_1 r_{PR}(\mathbf{X}, \varrho) + c_2 r_{SR}(\mathbf{Q}_s) \quad (17a)$$

$$\text{s.t.} \quad \|\mathbf{v}_{p,k}\|^2 \leq P_0, \quad \forall k, \quad (17a)$$

$$\text{Tr}(\mathbf{E}_k \mathbf{X}) \leq P_0, \quad \forall k, \quad (17b)$$

$$\text{Tr}(\mathbf{Q}_s) + \|\mathbf{w}_p\|^2 \leq \eta \varrho P_{EH}(\mathbf{X}), \quad (17c)$$

$$c_3 \eta \varrho \text{Tr}(\mathbf{H}_{EAP,ST} \mathbf{X} \mathbf{H}_{EAP,ST}^H) + c_4 |\mathbf{g}_{EAP,p}^H \mathbf{v}_p|^2 \leq C, \quad (17d)$$

$$0 \leq \varrho \leq 1, \quad (17e)$$

$$\mathbf{X} \succeq \mathbf{0}, \quad \mathbf{Q}_s \succeq \mathbf{0}, \quad (17f)$$

where  $\mathbf{E}_k = \text{Diag}([0, \dots, \mathbf{I}_k, \dots, 0])$ , in which  $\text{Diag}([\cdot])$  denotes a block diagonal matrix with the block matrices on the diagonal given in  $[\cdot]$ .

In the above problem (P1), (17a) and (17b) illustrates the per-EAP power constraint for information and power transfer, respectively; (17c) indicates the transmitting power constraint of the ST subject to its harvested power from the EAPs and the PT; finally (17d) constrains the cost budget of the CCRN system no more than a constant value  $C$ .

#### IV. JOINT OPTIMIZATION OF FD ENERGY BEAMFORMING AND DF RELAYING

We first remove the inner  $\max(\cdot)$  by recasting (P1) into the following problem, denoting the optimum value of (P1) by  $f^*$ .  $f^* = \max\{f_1^*, f_2^*\}$ , where  $f_1^*$  and  $f_2^*$  are the optimum value of two subproblems (P1.1) and (P1.2) defined as shortly. They render the achievable rate of the

first-slot DF relaying achieved by the ST, and the joint EAPs, respectively, depending on the fact whether  $(1 - \varrho)\mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\varrho, \mathbf{X})\mathbf{h}_{p,ST}$  is larger than  $\mathbf{h}_{p,EAP}^H \mathbf{B}^{-1}(\mathbf{X})\mathbf{h}_{p,EAP}$  or not.

Problem (P1.1) based on the epigraph reformulation is given by

$$\begin{aligned} \text{(P1.1)} : \quad & \max_{\mathbf{X}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p, \varrho, t} \quad \frac{1}{2}c_1 \log_2(1+t) + c_2 r_{SR}(\mathbf{Q}_s) \\ \text{s.t.} \quad & (17a) - (17e), \end{aligned} \tag{18a}$$

$$(1 - \varrho)P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\varrho, \mathbf{X})\mathbf{h}_{p,ST} \geq P_p \mathbf{h}_{p,EAP}^H \mathbf{B}^{-1}(\mathbf{X})\mathbf{h}_{p,EAP}, \tag{18b}$$

$$(1 - \varrho)P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\varrho, \mathbf{X})\mathbf{h}_{p,ST} \geq t, \tag{18c}$$

$$\frac{|\mathbf{g}_{sp}^H \mathbf{w}_p + \mathbf{g}_{EAP,p}^H \mathbf{v}_p|^2}{\mathbf{g}_{sp}^H \mathbf{Q}_s \mathbf{g}_{sp} + \sigma_{PR}^2} \geq t, \tag{18d}$$

$$\mathbf{X} \succeq \mathbf{0}, \mathbf{Q}_s \succeq \mathbf{0}, t \geq 0, \tag{18e}$$

where  $\mathbf{A}$  is related to the optimization variables  $\varrho$  and  $\mathbf{X}$ , and thus denoted by  $\mathbf{A}(\varrho, \mathbf{X})$  for the convenience of exposition, while  $\mathbf{B}$  is denoted by  $\mathbf{B}(\mathbf{X})$ .

(P1.2) is similarly given by

$$\begin{aligned} \text{(P1.2)} : \quad & \max_{\mathbf{X}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p, \varrho, t} \quad \frac{1}{2}c_1 \log_2(1+t) + c_2 r_{SR}(\mathbf{Q}_s) \\ \text{s.t.} \quad & (17a) - (17e), (18d) - (18e), \end{aligned} \tag{19a}$$

$$P_p \mathbf{h}_{p,EAP}^H \mathbf{B}^{-1}(\mathbf{X})\mathbf{h}_{p,EAP} \geq (1 - \varrho)P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\varrho, \mathbf{X})\mathbf{h}_{p,ST}, \tag{19b}$$

$$P_p \mathbf{h}_{p,EAP}^H \mathbf{B}^{-1}(\mathbf{X})\mathbf{h}_{p,EAP} \geq t. \tag{19c}$$

#### A. Problem Reformulation

It is observed that  $\mathbf{X}$  and  $\varrho$  are coupled together in (18b), (18c), and (17c), which make these constraints non-convex. Hence, we propose to solve problem (P1.1) in two stages as follows.

First, given  $\varrho = \bar{\varrho} \in [0, 1]$ , we solve the following problem.

$$\begin{aligned} \text{(P1.1-1)} : \quad & \max_{\mathbf{X}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p, t} \quad \frac{1}{2}c_1 \log_2(1+t) + c_2 r_{SR}(\mathbf{Q}_s) \\ \text{s.t.} \quad & (17a) - (17b), (18d) - (18e), \end{aligned} \tag{20a}$$

$$(1 - \bar{\varrho})P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X})\mathbf{h}_{p,ST} \geq P_p \mathbf{h}_{p,EAP}^H \mathbf{B}^{-1}(\mathbf{X})\mathbf{h}_{p,EAP}, \tag{20b}$$

$$(1 - \bar{\varrho})P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X})\mathbf{h}_{p,ST} \geq t, \tag{20c}$$

$$\text{Tr}(\mathbf{Q}_s) + \|\mathbf{w}_p\|^2 \leq \eta \bar{\varrho} P_{EH}(\mathbf{X}), \tag{20d}$$

$$c_3\eta\bar{\varrho}\text{Tr}(\mathbf{H}_{EAP,ST}\mathbf{X}\mathbf{H}_{EAP,ST}^H) + c_4|\mathbf{g}_{EAP,p}^H\mathbf{v}_p|^2 \leq C. \quad (20e)$$

Next, denoting the optimum value of problem (P1.1-1) as  $f_1(\varrho)$  in line with the notation for the optimum value of problem (P1.1), i.e.,  $f_1^*$ , the optimum  $\varrho$  can be found by solving (P1.1-2) :  $\max_{\varrho \in [0,1]} f_1(\varrho)$  via one-dimension search over  $\varrho$ , which guarantees an  $\epsilon$ -optimum<sup>1</sup> solution. Hence, we focus on solving (P1.1-1).

Note that since both  $\mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{h}_{p,ST}$ , denoted by  $g_1(\mathbf{X})$ , and  $\mathbf{h}_{p,EAP}^H \mathbf{B}^{-1}(\mathbf{X}) \mathbf{h}_{p,EAP}$ , denoted by  $g_2(\mathbf{X})$ , are proved to be convex functions w.r.t  $\mathbf{X}$  (see Appendix A), the constraints given by (20b) and (20c) are in general not convex. However, (20b) is seen to admit the form of difference of convex (D.C.) functions, which falls into the category of D.C. programming [20], and thus is solvable by employing D.C. iterations [21]. Specifically, we replace the left-hand-side (LHS) of (20b) ((20c)) with its first-order Taylor expansion w.r.t.  $\bar{\mathbf{X}}$ , since it is a global lower-bound estimator of the convex function  $g_1(\mathbf{X})$  and affine. Therefore, (20b) is transformed into the following convex constraint.

$$(1 - \bar{\varrho})P_p(g_1(\bar{\mathbf{X}}) - \Re\{\text{Tr}(\nabla_{\mathbf{X}}g_1(\bar{\mathbf{X}})(\mathbf{X} - \bar{\mathbf{X}}))\}) \geq P_p\mathbf{h}_{p,EAP}^H\mathbf{B}^{-1}(\mathbf{X})\mathbf{h}_{p,EAP}, \quad (21)$$

where  $\nabla_{\mathbf{X}}g_1(\mathbf{X})$ , given by

$$\nabla_{\mathbf{X}}g_1(\mathbf{X}) = -(1 - \bar{\varrho})\mathbf{H}_{EAP,ST}^H\mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X})\mathbf{h}_{p,ST}\mathbf{h}_{p,ST}^H\mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X})\mathbf{H}_{EAP,ST} \quad (22)$$

denotes the gradient matrix of  $g_1(\mathbf{X})$ . Accordingly, plugging the LHS of (21) into (20c), the constraint (20c) is also made convex as follows.

$$(1 - \bar{\varrho})P_p(g_1(\bar{\mathbf{X}}) - \Re\{\text{Tr}(\nabla_{\mathbf{X}}g_1(\bar{\mathbf{X}})(\mathbf{X} - \bar{\mathbf{X}}))\}) \geq t. \quad (23)$$

It is easy to verify that satisfaction of the constraints (21) and (23) implies feasibility of (20b) and (20c), but the converse is not necessarily true. Hence, (21) and (23) in general shrinks the feasible region of (P1.1-1) unless  $\mathbf{X}^* = \bar{\mathbf{X}}$ , and may only lead to its lower-bound solution, which will be discussed in detail later.

Next, we look into the constraint (18d), which is non-convex due to coupling  $\mathbf{Q}_s$  and  $t$ . To facilitate solving (P1.1-1), we decouple the numerator and the denominator of its LHS by

<sup>1</sup> $\epsilon$ -optimum means that  $\forall \epsilon > 0$ , to achieve an objective value in the  $\epsilon$ -neighbourhood of its optimum value, there always exists a corresponding one-dimension search step length.

introducing an auxiliary variable  $y > 0$  as follows.

$$|\mathbf{g}_{sp}^H \mathbf{w}_p + \mathbf{g}_{EAP,p}^H \mathbf{v}_p| \geq \sqrt{ty}, \quad (24)$$

$$\mathbf{g}_{sp}^H \mathbf{Q}_s \mathbf{g}_{sp} + \sigma_{PR}^2 \leq y, \quad (25)$$

which prove to be sufficient and necessary to replace (18d). However, as  $\sqrt{ty}$  is jointly concave w.r.t.  $t$  and  $y$  over  $t > 0$  and  $y > 0$ , (24) is still non-convex. To accommodate this constraint to the framework of convex optimization, we equivalently transform the LHS of (24) into a linear form based upon the following lemma.

**Lemma 4.1:** The optimum value of (P1.1) is attained when the solution of  $\mathbf{w}_p^*$  and  $\mathbf{v}_p^*$  satisfies  $\angle(\mathbf{g}_{sp}^H \mathbf{w}_p) = \angle(\mathbf{g}_{EAP,p}^H \mathbf{v}_p^*)$ .

*Proof:* Please refer to Appendix B. ■

In accordance with Lemma 4.1, we have the constraint (24) equivalently expressed as

$$\Re \{ \mathbf{g}_{sp}^H \mathbf{w}_p + \mathbf{g}_{EAP,p}^H \mathbf{v}_p \} \geq \sqrt{ty}. \quad (26)$$

It is easy to observe that (26) implies (24), and by rotating any solution  $\mathbf{w}_p^*$  and  $\mathbf{v}_p^*$  with a common angle of  $-\angle(\mathbf{g}_{sp}^H \mathbf{w}_p^*)$ , (24) also implies (26) without violating any other constraints.

To deal with the RHS of (26), i.e.,  $\sqrt{ty}$ , since it is jointly concave over  $t > 0$  and  $y > 0$ , its first-order Taylor expansion given by

$$\sqrt{ty} \leq \sqrt{\bar{t}\bar{y}} + \frac{1}{2} \sqrt{\frac{\bar{y}}{\bar{t}}} (t - \bar{t}) + \frac{1}{2} \sqrt{\frac{\bar{t}}{\bar{y}}} (y - \bar{y}) \quad (27)$$

serves as its upper-bound approximation, in which the equality holds if and only if  $t = \bar{t}$  and  $y = \bar{y}$ . Hence, (24) can be approximated by a convex constraint expressed as

$$\Re \{ \mathbf{g}_{sp}^H \mathbf{w}_p + \mathbf{g}_{EAP,p}^H \mathbf{v}_p \} \geq \sqrt{\bar{t}\bar{y}} + \frac{1}{2} \sqrt{\frac{\bar{y}}{\bar{t}}} (t - \bar{t}) + \frac{1}{2} \sqrt{\frac{\bar{t}}{\bar{y}}} (y - \bar{y}). \quad (28)$$

Finally, the non-convex problem (P1.1-1) is reformulated as the following convex problem.

$$\begin{aligned} \text{(P1.1-1')} : \quad & \max_{\mathbf{X}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p, t, y} \quad \frac{1}{2} c_1 \log_2(1+t) + c_2 r_{SR}(\mathbf{Q}_s) \\ \text{s.t.} \quad & (17a) - (17b), (18e), (21), (23), (25), (28), (20d) - (20e), (29a) \\ & y \geq 0. \end{aligned} \quad (29b)$$

Problem (P1.2) can also be similarly treated and transformed into a two-stage problem, for which we employ the first-order Taylor expansion of the convex function  $g_2(\mathbf{X})$  in the LHS

of (19b) and (19c), respectively, to serve as their lower-bound approximation. As is done with (20b) and (20c), given any  $\varrho = \bar{\varrho}$ , (19b) and (19c) can be approximated by

$$P_p(g_2(\bar{\mathbf{X}}) - \Re\{\text{Tr}(\nabla_{\mathbf{X}} g_2(\bar{\mathbf{X}})(\mathbf{X} - \bar{\mathbf{X}}))\}) \geq (1 - \bar{\varrho}) P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{h}_{p,ST}, \quad (30)$$

and

$$P_p(g_2(\bar{\mathbf{X}}) - \Re\{\text{Tr}(\nabla_{\mathbf{X}} g_2(\bar{\mathbf{X}})(\mathbf{X} - \bar{\mathbf{X}}))\}) \geq t, \quad (31)$$

respectively, where  $\nabla_{\mathbf{X}} g_2(\mathbf{X})$  is given by

$$\nabla_{\mathbf{X}} g_2(\mathbf{X}) = -\theta^2 \tilde{\mathbf{H}}_{TR}^H \mathbf{B}^{-1}(\mathbf{X}) \mathbf{h}_{p,EAP} \mathbf{h}_{p,EAP}^H \mathbf{B}^{-1}(\mathbf{X}) \tilde{\mathbf{H}}_{TR}. \quad (32)$$

In addition, (P1.2) shares the same constraint (18d) with (P1.1), which can be approximated by the same constraints given in (25) and (28). Hence, the corresponding main stage of solving (P1.2) is given as follows.

$$\begin{aligned} \text{(P1.2-1')} : \quad & \max_{\mathbf{X}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p, t, y} \quad \frac{1}{2} c_1 \log_2(1+t) + c_2 r_{SR}(\mathbf{Q}_s) \\ \text{s.t.} \quad & (17a) - (17b), (18e), (30) - (31), (25), (28), (20d) - (20e), (29b). \end{aligned}$$

### B. Proposed Iterative Solutions

Before continue to solving (P1), we investigate the feasibility of problem (P1.1-1') and ((P1.2-1')). Due to their similar structure, we mainly focus on the feasibility of (P1.1-1'), and then point out some key differences between these two problems in terms of their feasibility.

First, we solve the following feasibility problem to find a feasible  $\mathbf{X}$  to (P1.1-1').

$$\begin{aligned} \text{(P1.1-0)} : \quad & \text{Find a solution of } \mathbf{X} \text{ and } \mathbf{v}_p \\ \text{s.t.} \quad & (17b), (21), (20e), \end{aligned} \quad (34a)$$

$$\mathbf{X} \succeq \mathbf{0}. \quad (34b)$$

Note that it is guaranteed by this step that given  $\bar{\varrho}$ , a feasible  $\mathbf{X}$  to problem (P1) exists, since for an arbitrary  $\bar{\mathbf{X}}$  satisfying (17b) and (20e), either (21) or (30) must hold. Therefore, if the  $\bar{\mathbf{X}}$  fails to make (P1.1) feasible, it must make (P1.2) feasible.

Next, applying the returned  $\mathbf{X}$  in the above problem as a new initial point of  $\bar{\mathbf{X}}$ , we aim to find feasible  $t$  and  $y$  by solving the following problem.

$$\begin{aligned} \text{(P1.1-0')} : \quad & \text{Find a solution of } \mathbf{X}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p, t, \text{ and } y \\ \text{s.t.} \quad & (17a) - (17b), (18e), (21) - (23), (25), (28), (20d) - (20e), (29b). \end{aligned} \quad (35a)$$

It is worth noting that proper chosen of  $\bar{t}$  and  $\bar{y}$  is necessary to solve (P1.1-0'). For example, with  $\bar{\mathbf{X}}$  fixed,  $\bar{y}$  can be specified by  $\sigma_{PR}^2$ , and then  $\bar{t}$  is given by  $(0, \min\{(1 - \bar{\varrho})P_p g_1(\bar{\mathbf{X}}), (\gamma^*)^2/y\})$ , in which  $\gamma^*$  is the optimum value of the following problem.

$$\begin{aligned} \max_{\mathbf{w}_p, \mathbf{v}_p} \quad & \Re \{ \mathbf{g}_{sp}^H \mathbf{w}_p + \mathbf{g}_{EAP,p}^H \mathbf{v}_p \} \\ \text{s.t.} \quad & (17a), (20d), \\ & \|\mathbf{w}_p\|^2 \leq \eta \bar{\varrho} P_{EH}(\mathbf{X}). \end{aligned}$$

Since problem (P1.1-0) and (P1.1-0') are both easily observed to be convex problems, they can be optimally solved by some optimization toolboxes such as CVX [22]. Denoting  $\mathbf{X}$ ,  $t$  and  $y$  returned by (P1.1-0') by  $\bar{\mathbf{X}}^{(0)}$ ,  $\bar{t}^{(0)}$ , and  $\bar{y}^{(0)}$ , respectively, it is easily seen that (P1.1-1') is feasible if  $\mathbf{X}$ ,  $t$ , and  $y$  take the value of  $\bar{\mathbf{X}}^{(0)}$ ,  $\bar{t}^{(0)}$ , and  $\bar{y}^{(0)}$ , respectively. Hence, it safely arrives at a feasible problem (P1.1-1') with the initial points  $\{\bar{\mathbf{X}}^{(0)}, \bar{t}^{(0)}, \bar{y}^{(0)}\}$  specified as above mentioned.

*Remark 4.1:* Although initial points to problem (P1.2-1') can be found similarly, it is worth noting that compared with (30), (21) turns out to be more likely to be infeasible, since the LHS of (20b) is a monotonically decreasing function over  $\bar{\varrho} \in [0, 1]$ , and when  $\bar{\varrho} \rightarrow 1$ , it is hardly lower-bounded by the LHS of (21). To illustrate this, we consider the case that there is no  $\mathbf{X}$  satisfying (21) when  $\bar{\varrho} = 1$ . Hence, when infeasibility of (P1.1-0) is detected assuming that  $\varrho$  is searched in an increasing order, only (P1.2-1') needs to be solved for the rest of  $\bar{\varrho}$ .

Since (P1.1-1') and (P1.2-1') have been shown to be convex problems, and at least one of them is guaranteed to be feasible by initializing  $\{\bar{\mathbf{X}}^{(0)}, \bar{t}^{(0)}, \bar{y}^{(0)}\}$  as discussed above, a SCA-based algorithm is developed to solve (P1) as shown in Algorithm 1. The convergence behaviour of Algorithm 1 is assured by the following proposition.

*Proposition 4.1:* Monotonic convergence of solutions to problem (P1.1-1') and (P1.2-1') in Algorithm 1 is achieved, i.e.,  $1/2c_1 \log_2(1 + t^{(n)}) + c_2 r_{SR}(\mathbf{Q}_s^{(n)}) \geq 1/2c_1 \log_2(1 + t^{(n-1)}) + c_2 r_{SR}(\mathbf{Q}_s^{(n-1)})$ . Moreover, the converged solutions satisfy all the constraints as well as the Karush-Kuhn-Tucker (KKT) conditions of problem (P1.1-1) and (P1.2-1), respectively.

*Proof:* Please refer to Appendix C. ■

### C. Proposed ZF-Based Solutions

In this subsection, we propose an insightful suboptimal design that simplifies the receiving beamforming design of the full-duplex EAPs, i.e.,  $\mathbf{u}_2$ . It is seen from (6) that the incumbent

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**Algorithm 1** Proposed Algorithm for Solving Problem (P1)

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**Require:**  $\bar{\varrho}$ ;  $\text{flag}_{\text{ST}} = 1$

- 1: **if** both (P1.1-0) and (P1.1-0') are solvable **then**
  - 2:     **go to** 6
  - 3: **else**
  - 4:      $\text{flag}_{\text{ST}} = 0$ ;  $f_1(\bar{\varrho}) \leftarrow 0$
  - 5: **end if**
  - 6:  $n \leftarrow 0$ ; initialize  $\{\bar{\mathbf{X}}, \bar{t}, \bar{y}\}$  with  $\{\bar{\mathbf{X}}^{(0)}, \bar{t}^{(0)}, \bar{y}^{(0)}\}$  returned by problem (P1.1-0')
  - 7: **repeat**
  - 8:     Solve problem (P1.1-1') to obtain  $\{\mathbf{X}^{(n+1)}, t^{(n+1)}, y^{(n+1)}\}$
  - 9:     Update  $\{\bar{\mathbf{X}}^{(n+1)}, \bar{t}^{(n+1)}, \bar{y}^{(n+1)}\} \leftarrow \{\mathbf{X}^{(n+1)}, t^{(n+1)}, y^{(n+1)}\}$
  - 10:     $n \leftarrow n + 1$
  - 11: **until** convergence of the objective value of (P1.1-1')
  - 12:  $f_1(\bar{\varrho}) \leftarrow$  the optimum value of (P1.1-1')
  - 13: Obtain  $f_1^*$  by one-dimension search over  $\varrho$
  - 14: Solve problem (P1.2) using the SCA method similarly to obtain  $f_2^*$  by one-dimension search over  $\varrho$
- Ensure:**  $f^* = \max\{f_1^*, f_2^*\}$
- 

design of  $\mathbf{u}_2$  depends on  $\mathbf{X}$ , which means that there will be some additional central optimization resources induced to compute  $\mathbf{u}_2$  after the problem (P1) has been solved and the optimum  $\mathbf{X}$  has been returned. The broadcast of  $\mathbf{u}_2$  causes unfavourable delay particularly when  $N_{R,k}$ 's is large in practice. Hence, we design  $\mathbf{X}$  in such a way that the receiving beamforming  $\mathbf{u}_2$  can be locally decided.

To do so, let EAPs jointly decode the PT's message regardless of the residual LI. For example, which an arbitrary vector align with  $\mathbf{h}_{p,EAP}$  is chosen as  $\mathbf{u}_2$ , i.e.,  $\mathbf{u}_2 = \mu \mathbf{h}_{p,EAP}$ ,  $\mu \in \mathbb{R}$ . In this way, the jointly decoding can be locally implemented with the  $k$ th EAP having already estimated and known the CSI of  $\mathbf{h}_{p,EAP_k}$ 's. Accordingly, the resulting receiving SINR at the EAPs coincides with its maximum, i.e.,  $P_p \|\mathbf{h}_{p,EAP}\|^2 / \sigma_{EAP}^2$ , if and only iff (iff)  $\mathbf{u}_2^H \tilde{\mathbf{H}}_{TR} \mathbf{X} \tilde{\mathbf{H}}_{TR}^H \mathbf{u}_2 = 0$ . Combining with  $\mathbf{u}_2 = \mu \mathbf{h}_{p,EAP}$ ,  $\mathbf{X}$  needs to be designed such that  $\mathbf{h}_{p,EAP}^H \tilde{\mathbf{H}}_{TR} \mathbf{X} \tilde{\mathbf{H}}_{TR}^H \mathbf{h}_{p,EAP} = 0$ . Defining  $\mathbf{h} = \tilde{\mathbf{H}}_{TR}^H \mathbf{h}_{p,EAP}$  with its normalized vector denoted by  $\bar{\mathbf{h}}$ , the projection matrix  $\mathbf{P} = \mathbf{I} - \bar{\mathbf{h}} \bar{\mathbf{h}}^H$  can be alternatively expressed as  $\mathbf{P} = \tilde{\mathbf{U}} \tilde{\mathbf{U}}^H$  with  $\tilde{\mathbf{U}} \in \mathbb{C}^{\sum N_{T,k} \times (\sum N_{T,k} - 1)}$  such that  $\bar{\mathbf{h}}^H \tilde{\mathbf{U}} = 0$  and  $\tilde{\mathbf{U}}^H \tilde{\mathbf{U}} = \mathbf{I}$ . The optimum structure of  $\mathbf{X}$  is then specified by the following lemma [23, Lemma 3.1].



**Lemma 4.2:** The optimum  $\mathbf{X}$  to (P1) is given by

$$\mathbf{X} = \tilde{\mathbf{U}} \tilde{\mathbf{X}} \tilde{\mathbf{U}}^H, \quad (36)$$

where  $\tilde{\mathbf{X}} \in \mathbb{C}^{(\sum N_{T,k}-1) \times (\sum N_{T,k}-1)}$  is a PSD matrix.

Applying Lemma 4.2 to Problem (P1.1), Problem (P1.1-1') can be reduced to

$$\begin{aligned} \text{(P1.1-1'-ZF)} : \quad & \max_{\tilde{\mathbf{X}}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p, t, y} \frac{1}{2} c_1 \log_2(1+t) + c_2 r_{SR}(\mathbf{Q}_s) \\ \text{s.t.} \quad & (17a), (25), (28), \end{aligned} \quad (37a)$$

$$\text{Tr}(\tilde{\mathbf{U}}^H \mathbf{E}_k \tilde{\mathbf{U}} \tilde{\mathbf{X}}) \leq P_0, \quad \forall k, \quad (37b)$$

$$\begin{aligned} & (1 - \bar{\varrho}) P_p \left( \tilde{g}_1(\bar{\mathbf{X}}) - \Re \left\{ \text{Tr} \left( \nabla_{\mathbf{X}} \tilde{g}_1(\bar{\mathbf{X}}) (\tilde{\mathbf{X}} - \bar{\mathbf{X}}) \right) \right\} \right) \\ & \geq P_p \|\mathbf{h}_{p,EAP}\|^2 / \sigma_{EAP}^2, \end{aligned} \quad (37c)$$

$$(1 - \bar{\varrho}) P_p \left( \tilde{g}_1(\bar{\mathbf{X}}) - \Re \left\{ \text{Tr} \left( \nabla_{\mathbf{X}} \tilde{g}_1(\bar{\mathbf{X}}) (\tilde{\mathbf{X}} - \bar{\mathbf{X}}) \right) \right\} \right) \geq t, \quad (37d)$$

$$\text{Tr}(\mathbf{Q}_s) + \|\mathbf{w}_p\|^2 \leq \eta \bar{\varrho} P_{EH}(\tilde{\mathbf{U}} \tilde{\mathbf{X}} \tilde{\mathbf{U}}^H), \quad (37e)$$

$$c_3 \eta \bar{\varrho} \text{Tr}(\mathbf{H}_{EAP,ST} \tilde{\mathbf{U}} \tilde{\mathbf{X}} \tilde{\mathbf{U}}^H \mathbf{H}_{EAP,ST}^H) + c_4 |\mathbf{g}_{EAP,p}^H \mathbf{v}_p|^2 \leq C, \quad (37f)$$

$$\tilde{\mathbf{X}} \succeq \mathbf{0}, \mathbf{Q}_s \succeq \mathbf{0}, t \geq 0, y \geq 0, \quad (37g)$$

where  $\tilde{g}_1(\mathbf{X}) = g_1(\tilde{\mathbf{U}} \tilde{\mathbf{X}} \tilde{\mathbf{U}}^H)$ , and  $\nabla_{\mathbf{X}} \tilde{g}_1(\mathbf{X})$  denotes the gradient matrix of  $\tilde{g}_1(\mathbf{X})$  expressed as  $\nabla_{\mathbf{X}} \tilde{g}_1(\mathbf{X}) =$

$$-(1 - \bar{\varrho}) \tilde{\mathbf{U}}^H \mathbf{H}_{EAP,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \tilde{\mathbf{U}} \tilde{\mathbf{X}} \tilde{\mathbf{U}}^H) \mathbf{h}_{p,ST} \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \tilde{\mathbf{U}} \tilde{\mathbf{X}} \tilde{\mathbf{U}}^H) \mathbf{H}_{EAP,ST} \tilde{\mathbf{U}}. \quad (38)$$

Similarly, Problem (P1.2-1') reduces to the following problem.

$$\begin{aligned} \text{(P1.2-1'-ZF)} : \quad & \max_{\tilde{\mathbf{X}}, \mathbf{Q}_s, \mathbf{w}_p, \mathbf{v}_p, t, y} \frac{1}{2} c_1 \log_2(1+t) + c_2 r_{SR}(\mathbf{Q}_s) \\ \text{s.t.} \quad & (17a) - (17b), (25), (28), (37e) - (37g), \end{aligned} \quad (39a)$$

$$\frac{P_p \|\mathbf{h}_{p,EAP}\|^2}{\sigma_{EAP}^2} \geq (1 - \bar{\varrho}) P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \tilde{\mathbf{U}} \tilde{\mathbf{X}} \tilde{\mathbf{U}}^H) \mathbf{h}_{p,ST}, \quad (39b)$$

$$\frac{P_p \|\mathbf{h}_{p,EAP}\|^2}{\sigma_{EAP}^2} \geq t. \quad (39c)$$

Note that compared with (P1.2-1'), (P1.2-1'-ZF) admits a substantially simplified exposition because not only is there no more variable related to  $\mathbf{X}$  in the LHS of (39b) and (39c), but also they turn out to be convex. This means that there is no approximation made w.r.t  $\mathbf{X}$ , and thus

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**Algorithm 2** Proposed ZF-Based Algorithm for Solving Problem (P1)

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- 1: Find feasible  $\{\tilde{\mathbf{X}}, t, y\}$  to (P1.1-1'-ZF) as the initial  $\{\tilde{\mathbf{X}}^{(0)}, \bar{t}^{(0)}, \bar{y}^{(0)}\}$
- 2: Solve (P1.1-1'-ZF) using the SCA method
- 3: Solve (P1.1) to obtain  $f_1^*$  by one-dimension search over  $\varrho$
- 4: Find feasible  $\{t, y\}$  to (P1.2-1'-ZF) as the initial  $\{\bar{t}^{(0)}, \bar{y}^{(0)}\}$
- 5: Solve (P1.2-1'-ZF) using the SCA method
- 6: Solve (P1.2) to obtain  $f_2^*$  by one-dimension search over  $\varrho$

**Ensure:**  $f^* = \max\{f_1^*, f_2^*\}$

---

(P1.2-1'-ZF) is expected to converge faster, since there are only two iterated variables remained,  $t$  and  $y$ . As the ZF-based solutions are obtained from reduced problems from (P1), the solution and the convergence analysis are thus similar to Algorithm 1. Hence, we only present an outline of the algorithm for the proposed ZF-based solutions which shown in Algorithm 2.

## V. BENCHMARK SCHEMES

In this section, two benchmark schemes are presented, where only one of the available EAPs operating in FD mode is selected to assist with the CCRN, and all the EAPs work together but operate in HD mode, respectively.

### A. Selective Non-cooperative FD Scheme

First, consider the case when only one EAP is selected in the CCRN. This is the case when joint transmission and/or detection of the WPT and WIT signals is expensive or unavailable due to extra resources (e.g., spectrum, power, centralized coordination point) and strict synchronization requirement among EAPs. The selection of the EAP is based on a simple criterion:  $\tilde{k} = \arg \max_{k \in \mathcal{K}} \|\mathbf{h}_{p,EAP_k}\|^2$ . Note that by replacing  $\mathbf{h}_{p,EAP}(\mathbf{g}_{EAP,p})$  with  $\mathbf{h}_{p,EAP_{\tilde{k}}}(\mathbf{g}_{EAP_{\tilde{k}},p})$ , solving the resulting (P1) follows the same procedure as those detailed in Section IV-B, and thus is omitted here for brevity.

### B. HD EB and DF Relaying

Next, consider the case when all the EAPs work under the HD mode. In this case, as DF relaying only takes place at the ST,  $r_{PR}(\mathbf{X}, \varrho)$  reduces to

$$r'_{PR}(\mathbf{X}, \varrho) = \frac{1}{2} \log_2 \left( 1 + \min \left\{ (1 - \varrho) P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1} \mathbf{h}_{p,ST}, \frac{|\mathbf{g}_{sp}^H \mathbf{w}_p|^2}{\mathbf{g}_{sp}^H \mathbf{Q}_s \mathbf{g}_{sp} + \sigma_{PR}^2} \right\} \right). \quad (40)$$

Moreover, the total cost constraint for the HD EAPs-aiding CCRN is also simplified as

$$c_3\eta\varrho\text{Tr}(\mathbf{H}_{EAP,ST}\mathbf{X}\mathbf{H}_{EAP,ST}^H) \leq C. \quad (41)$$

Accordingly, (P1) can be equivalently recast into the following problem.

$$\begin{aligned} \text{(P1-HD)} : \quad & \max_{\mathbf{X}, \mathbf{Q}_s, \mathbf{w}_p, \varrho, t} \quad \frac{1}{2}c_1 \log_2(1+t) + c_2 r_{SR}(\mathbf{Q}_s) \\ \text{s.t.} \quad & (17b) - (17c), (18c), (17e) - (18e), (41), \end{aligned} \quad (42)$$

$$\frac{|g_{sp}^H \mathbf{w}_p|^2}{g_{sp}^H \mathbf{Q}_s g_{sp} + \sigma_{PR}^2} \geq t. \quad (43)$$

Compared with solving (P1), we use a slightly different approach to solve (P1-HD) in view of its structure. Note from (P1-HD) that as  $t$  increases, the objective value of (P1-HD) becomes larger at first. However, continuously increasing  $t$  will eventually violate (18c) and/or (43), since the LHS of both of them are easily shown to be upper-bounded. On the other hand, it is observed that a large enough  $t$  obtained by suppressing the value of  $\text{Tr}(\mathbf{Q}_s)$  may also compromise the value of  $r_{SR}(\mathbf{Q}_s)$ . Hence, it suggests that there exists a proper  $t$  that achieves the optimum value of (P1-HD). Given  $\varrho = \bar{\varrho}$  and  $t = \bar{t}$ , denote the optimum value of the following problem by  $f'_1(\bar{\varrho}, \bar{t})$ .

$$\begin{aligned} \text{(P1-HD-SDR)} : \quad & \max_{\mathbf{X}, \mathbf{Q}_s, \mathbf{W}_p} \quad \frac{1}{2}c_1 \log_2(1+\bar{t}) + c_2 r_{SR}(\mathbf{Q}_s) \\ \text{s.t.} \quad & (17b), (23), \end{aligned} \quad (44)$$

$$\text{Tr}(\mathbf{G}_{sp} \mathbf{W}_p) \geq \bar{t} (g_{sp}^H \mathbf{Q}_s g_{sp} + \sigma_{PR}^2), \quad (45)$$

$$\text{Tr}(\mathbf{Q}_s + \mathbf{W}_p) \leq \eta \bar{\varrho} P_{EH}(\mathbf{X}), \quad (46)$$

$$c_3\eta\bar{\varrho}\text{Tr}(\mathbf{H}_{EAP,ST}\mathbf{X}\mathbf{H}_{EAP,ST}^H) \leq C, \quad (47)$$

$$\mathbf{X} \succeq \mathbf{0}, \mathbf{Q}_s \succeq \mathbf{0}, \mathbf{W}_p \succeq \mathbf{0}, \quad (48)$$

where  $\mathbf{G}_{sp} = \mathbf{g}_{sp}\mathbf{g}_{sp}^H$ , and  $\mathbf{W}_p = \mathbf{w}_p\mathbf{w}_p^H$  with its constraint  $\text{rank}(\mathbf{W}_p) = 1$  removed. Then we have the following lemma that can be derived through strong duality [24, Appendix A].

**Lemma 5.1:**  $f'_1(\varrho, t)$  is a concave function w.r.t  $t$ .

Note that given  $\varrho = \bar{\varrho}$  and  $t = \bar{t}$ , (23) implies (18c), and therefore leads to a lower-bound solution to (P1-HD), while imposing rank relaxation on  $\mathbf{W}_p$  in general enlarges its feasible region and thus yields an upper-bound solution to (P1-HD). The final effect of these two transformation on the objective value of problem (P1-HD) is nevertheless of no ambiguity,

since the tightness of the semi-definite relaxation in the latter holds because of the following proposition.

*Proposition 5.1:* The optimal solution to problem (P1-HD-SDR) satisfies  $\text{rank}(\mathbf{W}_p^*) = 1$  such that  $\mathbf{W}_p^* = \mathbf{w}_p^* \mathbf{w}_p^{*H}$ .

*Proof:* The proof for the rank-one property of  $\mathbf{W}^*$  is similar to [16, Appendix A], and is thus omitted here due to the length constraint of the paper. ■

Hence, we solve (P1-HD) by two-dimension search over  $\varrho$  and  $t$ , i.e.,  $f'^* = \max_{\varrho, t} f'_1(\varrho, t)$ , where  $t$  can be found by some low complexity search such as bi-section algorithm in accordance with Lemma 5.1. Specifically, given each  $\varrho$  and  $t$ , an SDR problem shown in (P1-HD-SDR) is solved by the SCA method in analogue to that adopted by Algorithm 1.

## VI. NUMERICAL RESULTS

In this section, we evaluate the proposed joint EB and DF relaying aided by multiple full-duplex EAPs in the CCRN against the benchmark schemes. The proposed iterative solutions and the ZF-based solutions for solving (P1) in Section IV-B and Section IV-C are denoted by “FD Optimal” and “FD-ZF”, respectively. For the benchmarks, the non-cooperative scheme with only one EAP associated with the ST in Section V-A is denoted by “FD Non-cooperative”, while the HD case introduced in Section V-B is denoted by “HD”.

In the following numerical examples, the parameters are set as follows unless otherwise specified. As illustrated in Fig. 1, there is one PT, one PR, each with one single antenna, and multi-antenna ST and SR equipped with  $M = 2$  and  $N = 2$  antennas, respectively. There are also  $K = 3$  EAPs each equipped with  $L = 4$  antennas, among which half of them are specified as transmitting antennas and the other half as receiving antennas, i.e.,  $N_{T,1} = N_{T,2} = N_{T,3} = 2$  and  $N_{R,1} = N_{R,2} = N_{R,3} = 2$ . The distance from the ST to the PT, PR, and SR are set as  $d_{p,ST} = 10\text{m}$ ,  $d_{sp} = 10\text{m}$  and  $d_{ss} = 10\text{m}$ . The EAPs are located within a circle centred on the ST with their radius uniformly distributed over  $[0, 10]\text{m}$ . The generated wireless channels consist of both large-scale path loss and small-scale multi-path fading. The pathloss model is given by  $A_0(d/d_0)^{-\alpha}$  with  $A_0 = -30\text{dB}$ , where  $d$  denotes the relevant distance,  $d_0 = 1\text{m}$  is a reference distance, and  $\alpha = 2.5$  is the path loss exponent factor. The small-scale fading follows *i.i.d.* Rayleigh fading with zero mean and unit variance. The effective residual LI channel gain  $\theta^2$  is set to be  $-60\text{dB}$ . The weight coefficients are assumed to be  $c_1 = c_2 = 1$ ,  $c_3 = 1$  and  $c_4 = 1$  are adopted for the cost per unit of received energy for WPT and WIT, respectively. The normalized

cost, defined by  $C/C_{\max}$ , is set to be 0.1. The transmitting power is set as  $P_p = 10\text{dBm}$  and  $P_0 = 20\text{dBm}$ . The other parameters are set as follows. The RF-band AWGN noise and the RF-band to baseband conversion noise are set to be  $\sigma_{n_a}^2 = -110\text{dBm}$  and  $\sigma_{n_c}^2 = -70\text{dBm}$ , respectively;  $\sigma_{EAP}^2 = \sigma_{PR}^2 = \sigma_{SR}^2$  are all set equal to  $\sigma_{n_a}^2 + \sigma_{n_c}^2$ ; the EH efficiency is set as  $\eta = 50\%$  [25]. The evaluation in the following examples are averaged over 300 independent channel realizations.

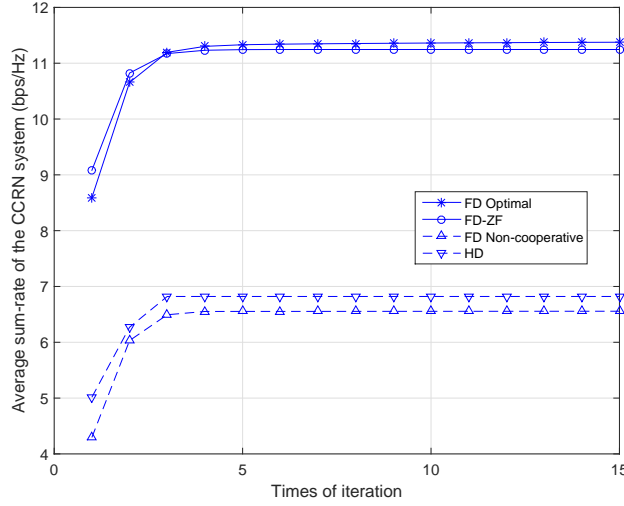


Fig. 2. The average sum-rate of the CCRN system versus the times of iteration of the SCA algorithm by the four schemes, in which  $c_1 = c_3 = c_4 = 1$  and  $c_2 = 10$ .

Fig. 2 shows the convergence behaviour of the proposed iterative algorithm, which is guaranteed by Proposition 4.1. It is also seen that the number of iterations for the proposed and suboptimal schemes to converge is around within 10, while those for the benchmark schemes ‘FD Non-cooperative’ and ‘HD’ are less than 5. It is also observed that there is only little performance gap between “FD-ZF” solutions and “FD Optimal” solutions.

Fig. 3 shows the instantaneous sum-rate of the system achieved by different schemes and the associated values of the PS factor  $\varrho$  in some special cases. In Example 1, There are  $K = 2$  EAPs located on the right of the ST alongside the PT-ST direction, with 10m and 20m away from the ST, respectively;  $d_{p,ST} = 5\text{m}$ ;  $N = 4$ ;  $\theta^2 = -40\text{dB}$ ;  $c_3 = 10$ ; the normalized cost constraint is 0.01. The optimal  $\varrho$  for all the cases except the “HD” is about 0.9, which means that the ST does not exploit its full EH capability. This is mainly due to the following two reasons. On one hand, since  $\mathbf{h}_{p,ST}$  is better than  $\mathbf{h}_{p,EAP}$ , the optimum value of  $f$  is achieved by  $f_1^*$ , which means

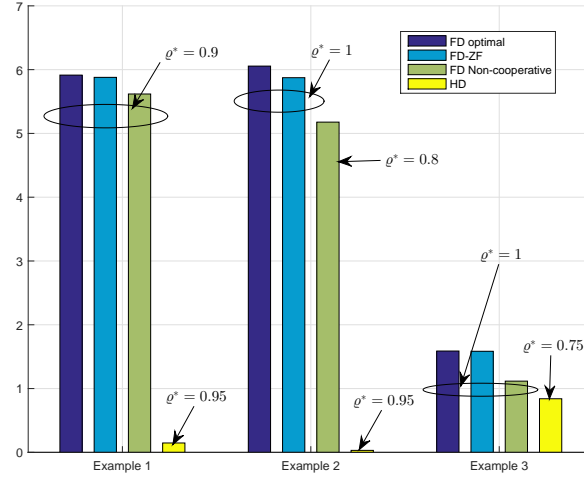


Fig. 3. The instantaneous sum-rate of the CCRN system achieved by different schemes in special scenarios, in which  $P_0 = 23\text{dBm}$  and  $P_1 = 20\text{dBm}$ .

that the constraint in (18c) is active. As a result, continuing increasing  $\varrho$  will violate (18c), since it is not hard to prove that the LHS of is a monotonically decreasing function w.r.t  $\varrho \in [0, 1)$ . On the other hand, since  $c_3$  is as ten times large as  $c_4$ , which means that the unit price required by WPT is quite high, the system intuitively prefers to saving the amount of harvested power in this budget-limited case. In Example 2, there are  $K = 3$  EAPs uniformly located on a circle of radius 10m centred on the ST, respectively,  $d_{p,ST} = 10\text{m}$ , and all the other settings are the same as those in Example 1. It is seen that the optimal  $\varrho$  is one in this case for both of the “FD Optimal” and “FD-ZF” scheme, which is apparently due to the good channel conditions of  $h_{p,EAP}$ , and the enhanced  $\mathbf{H}_{EAP,ST}$ , which encourages the system to fully exploit this good condition of being charged by EAPs.

Example 3 explores the other special case when “HD” scheme also performs reasonably well. In this case there are  $K = 5$  EAPs uniformly distributed on a circle of radius 5m centred on the ST;  $d_{ss} = 5\text{m}$ ;  $L = 2$ ,  $c_1 = 0.1$ ,  $c_2 = 1.9$ , and  $c_4 = 100$ ; the normalized cost constraint is 0.001. Note that this case emulates the scenario when the weighted sum-rate imposes priority on the secondary system subject to a quite limited cost budget. It is observed that since the secondary system’s rate is contributed by the ST’s harvested power, the priority in favour of the ST’s transmission is achieved by splitting all its received power for EH while leaving the task of relaying the PT’s message to the EAPs.

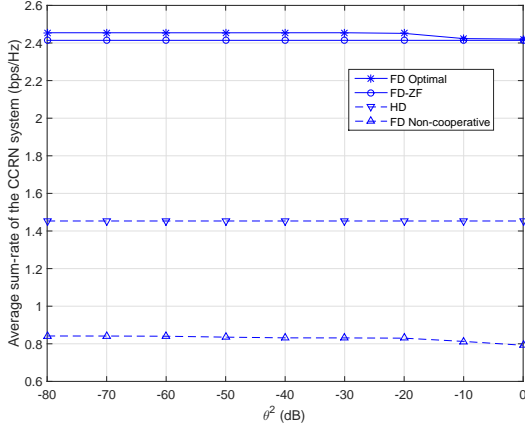
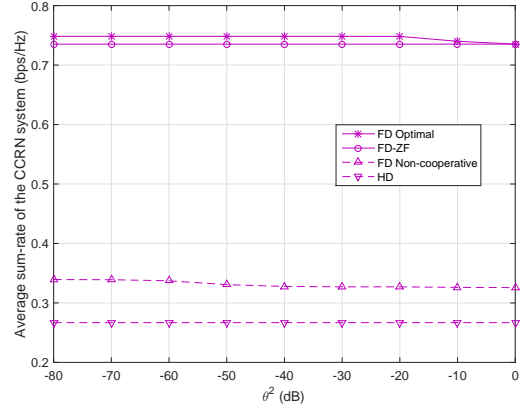
(a)  $C/C_{\max} = 0.1$ (b)  $C/C_{\max} = 0.01$ 

Fig. 4. The average sum-rate of the CCRN system versus the residue power level of the LI, in which  $d_{p,ST} = 15\text{m}$ ,  $d_{sp} = 10\text{m}$ ,  $d_{ss} = 10\text{m}$ ,  $c_1 = 0.1$ ,  $c_2 = 1.9$ ,  $c_3 = 0.1$ , and  $c_4 = 10$ ; the  $K = 3$  EAPs are located within a ST-centred circle with their radius uniformly distributed over  $[0, 5]\text{m}$ .

Fig. 4 reflects the impact of the residue power of LI on the average sum-rate of the system subject to different normalized cost constraints by different schemes. It is observed that the FD schemes are in general quite robust against the increasing power of LI. It is also seen that the suboptimal “FD-ZF” is outperformed by the proposed scheme in most cases, but approaches “FD Optimal” with negligible gap when  $\theta^2$  is larger than  $-20\text{dB}$ . In addition, “FD-ZF” and “HD” schemes remain exactly the same, since their designs are irrelevant of  $\theta^2$ . Moreover, it is intriguing to see that “HD” considerably outperforms “FD Non-cooperative” in Fig. 4(a), and reversely performs in Fig. 4(b). This can be explained as follows. As a result of the transmission priority imposed on the secondary system ( $c_1 = 0.1$ ,  $c_2 = 1.9$ ), as well as the relatively cheaper per unit price for WPT ( $c_3 = 0.1$ ,  $c_4 = 10$ ), the system tends to power the ST for improving on its own transmission as much as possible. Hence, when there is enough cost budget, the WPT capability of “HD” is larger than that of “FD Non-cooperative”, which leads to a larger objective value that is dominated by the SR’s contribution in this case.

Fig. 5 illustrates the average sum-rate of the system achieved by different schemes versus the normalized cost constraints with different weights of the sum-rate. It is observed that the average sum-rate of the system goes up drastically when the transmission is in favour of the ST, which is mainly caused by the imbalanced transmission efficiency between WPT and WIT. It is also observed that “FD-ZF” performs nearly as well as the proposed “FD Optimal” scheme when the

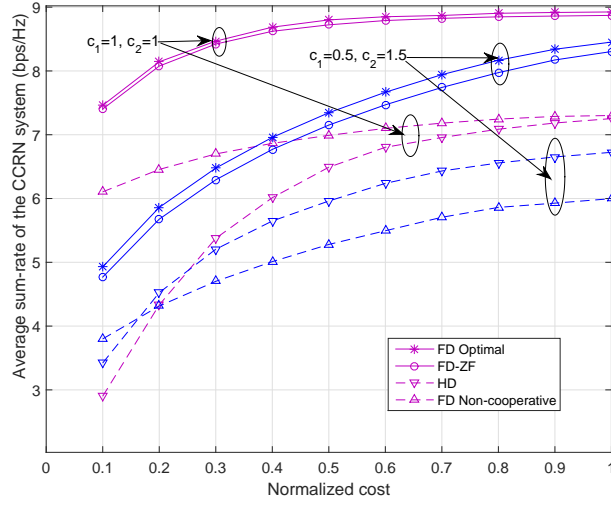


Fig. 5. The average sum-rate of the CCRN system versus the normalized cost budget, in which  $K = 2$ ,  $N = 6$ ,  $c_1 = 0.5$ , and  $c_2 = 1.5$ .

primary and the secondary system share the same weights of sum-rate. This is because when  $r_{SR}(\mathbf{Q}_s)$  contributes more to the sum-rate ( $c_1 = 0.5$ ,  $c_2 = 1.5$ ), the requirement of increasing  $\text{Tr}(\mathbf{Q}_s)$  leads to the fact that the WPT plays a more important role in the CCRN, and therefore the suboptimal design of the WPT transmission will compromise the objective value.

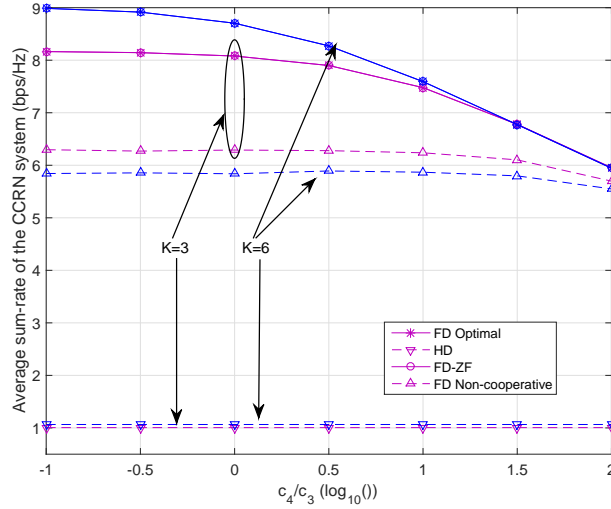


Fig. 6. The average sum-rate of the CCRN system versus the unit price of WIT normalized by that of WPT, in which  $P_p = 20\text{dBm}$  and there is a constant total cost  $C$  set to be 3.



The way that the unit price of the received energy for WIT versus WPT affects the average sum-rate of the system by different schemes is shown in Fig. 6. It is seen that “FD-ZF” approaches the proposed “FD optimal” scheme with a negligible gap, and both of them fall over the increasing per-unit cost for WIT, with the superior scheme of  $K = 6$  eventually decreasing to nearly the same value as that for  $K = 3$ . These observations are particularly useful when the cost for WIT is higher than that for WPT, which is usually the case in practice, since compared to coordinated WPT relying on random energy beams, it costs the EAPs more to perform WIT. In addition, “FD Non-cooperative” with  $K = 6$  EAPs is outperformed by that with  $K = 3$  EAPs, which reveals that the  $\max_{k \in \mathcal{K}} \|\mathbf{h}_{p,EAP_k}\|^2$ -based non-cooperative scheme is not an optimal strategy to fully exploit the diversity gains, since it only benefits the first hop of the DF relaying. In other words, the EAP with  $\max_{k \in \mathcal{K}} \|\mathbf{h}_{p,EAP_k}\|^2$  does not necessarily possess the maximum  $\|\mathbf{g}_{EAP_k,p}\|^2$  (c.f. (11)), if not worse.

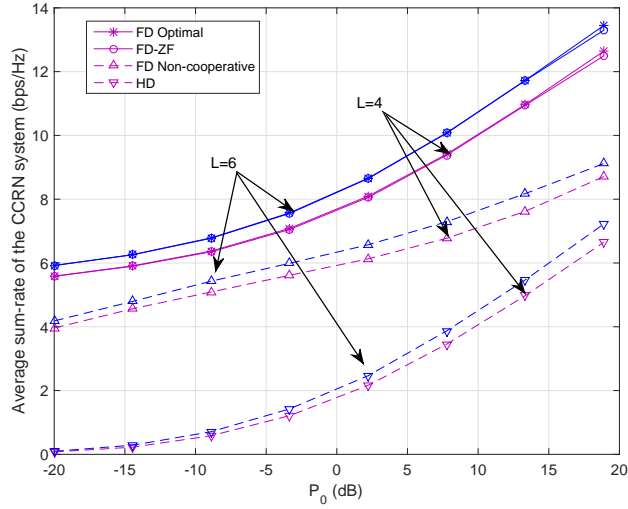


Fig. 7. The average sum-rate of the CCRN system versus the per-EAP transmit power constraint, in which  $L = 6$ .

The benefit of increasing per-EAP transmission power for the average sum rate of the system achieved by different schemes is shown in Fig. 7. It is seen that with larger number of antennas equipped at each EAP, better performance is achieved due to the increasing array gain. It is also noticed that “FD-ZF” keeps up with “FD Optimal” with a negligible gap until  $P_0$  increases to 20dB. Moreover, for both cases of  $L = 4$  and  $L = 6$ , it is observed that the average-sum rates achieved by all the schemes other than “FD Non-cooperative” go up quickly as a result of the substantially enlarged feasible region (c.f. (17a)-(17b)). Furthermore, the advantage of “FD Non-

cooperative” over HD is more and more limited with the increasing  $P_0$  especially when  $L = 6$ , since the increasing WEH capability gained by  $L \times K$  antennas in “HD” versus  $L$  antennas in “FD Non-cooperative” well compensates for its HD limitation in high  $P_0$  regime.

## VII. CONCLUSION

This paper investigates two techniques to fundamentally improve the spectrum efficiency of the RF EH-enabled CCRN, namely, dedicated EB and FD relaying provided by multi-antenna EAPs. Specifically, assuming a, the EAPs jointly transfer wireless power to the ST while decoding PT’s message in the first transmission phase; the EAPs cooperate to forward PT’s message and the ST superimposes PT’s message on its own to broadcast in the second transmission phase. The EAPs’ energy beams as well as their receiving and transmitting beamforming for PT’s message and ST’s PS ratio as well as its transmitting beamforming are jointly optimized to maximize the weighted sum-rate taking both energy and cost constraints into account. The proposed algorithms using SCA techniques are proved to converge with the KKT conditions of the corresponding problems satisfied. The promising EB design based on ZF is shown to be near-optimal. Other benchmark schemes are also provided to validate the effectiveness of the proposed schemes.

## APPENDIX A CONVEXITY OF (20b)

First, the gradient of  $g_1(\mathbf{X})$  w.r.t  $\mathbf{X}$  is expressed as

$$\nabla_{\mathbf{X}} g_1(\mathbf{X}) = -(1 - \bar{\varrho}) \mathbf{H}_{EAP,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{h}_{p,ST} \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{H}_{EAP,ST}. \quad (49)$$

Before obtaining the Hessian matrix of  $g_1(\mathbf{X})$  w.r.t  $\mathbf{X}$ , we derive the derivative matrix of (49) as follows.  $D(\nabla_{\mathbf{X}} g_1(\mathbf{X})) =$

$$\begin{aligned} & (1 - \bar{\varrho}) \mathbf{H}_{EAP,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) D(\mathbf{A}(\bar{\varrho}, \mathbf{X})) \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{h}_{p,ST} \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{H}_{EAP,ST} \\ & + (1 - \bar{\varrho}) \mathbf{H}_{EAP,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{h}_{p,ST} \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) D(\mathbf{A}(\bar{\varrho}, \mathbf{X})) \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{H}_{EAP,ST}. \end{aligned} \quad (50)$$

Next, in line with the equality  $D(\mathbf{A}(\bar{\varrho}, \mathbf{X})) = (1 - \bar{\varrho}) \mathbf{H}_{EAP,ST} D\mathbf{X} \mathbf{H}_{EAP,ST}^H$ , it follows that

$$\nabla_{\mathbf{X}}^2 g_1(\mathbf{X}) = (1 - \bar{\varrho})^2 (\mathbf{A}_1^T(\bar{\varrho}, \mathbf{X}) \otimes \mathbf{A}_2(\bar{\varrho}, \mathbf{X}) + \mathbf{A}_2^T(\bar{\varrho}, \mathbf{X}) \otimes \mathbf{A}_1(\bar{\varrho}, \mathbf{X})), \quad (51)$$

where  $\mathbf{A}_1(\bar{\varrho}, \mathbf{X})$  is given by

$$\mathbf{A}_1(\bar{\varrho}, \mathbf{X}) = \mathbf{H}_{EAP,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{h}_{p,ST} \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{H}_{EAP,ST}, \quad (52)$$

and  $\mathbf{A}_2 = \mathbf{H}_{EAP,ST}^H \mathbf{A}^{-1}(\bar{\varrho}, \mathbf{X}) \mathbf{H}_{EAP,ST}$ .

We can now determine the convexity of  $g_1(\mathbf{X})$  by studying the semidefiniteness of  $\nabla_{\mathbf{X}}^2 g_1(\mathbf{X})$  [26]. Take  $\mathbf{A}_1^T \otimes \mathbf{A}_2$  as an example, Since  $\lambda_l(\mathbf{A}_1^T \otimes \mathbf{A}_2) = \lambda_l(\mathbf{A}_1^T) \lambda_l(\mathbf{A}_2) \geq 0$  [27], where  $\lambda_l(\cdot)$  denotes the  $l$ th non-zero eigenvalue of the associate matrix ( $l = 1$  herein), it turns out that  $\mathbf{A}_1^T \otimes \mathbf{A}_2$  is a PSD matrix and so is  $\mathbf{A}_2^T \otimes \mathbf{A}_1$ . Hence  $\nabla_{\mathbf{X}}^2 g_1(\mathbf{X})$  is proved to be PSD and so is  $\nabla_{\mathbf{X}}^2 g_2(\mathbf{X})$ , which completes the proof.

## APPENDIX B

### PROOF OF LEMMA 4.1

This can be proved by contradiction. Assuming the optimum value of problem (P1.1) is achieved by  $\mathbf{X}^*, \mathbf{Q}^*, \mathbf{w}_p^*, \mathbf{v}_p^*, t^*$  and  $\varrho^*$  such that  $\angle(\mathbf{g}_{sp}^H \mathbf{w}_p^*) \neq \angle(\mathbf{g}_{EAP,p}^H \mathbf{v}_p^*)$ . In other words,  $\exists \mathbf{w}_p' = \mathbf{w}_p^* \exp\{j\angle\theta\}$ , where  $\theta \neq 2n\pi$ ,  $n \in \mathbb{Z}$ , such that  $\angle(\mathbf{g}_{sp}^H \mathbf{w}_p') = \angle(\mathbf{g}_{EAP,p}^H \mathbf{v}_p^*)$ . Hence, it follows that

$$\begin{aligned} |\mathbf{g}_{sp}^H \mathbf{w}_p' + \mathbf{g}_{EAP,p}^H \mathbf{v}_p^*| &= (|\mathbf{g}_{sp}^H \mathbf{w}_p'| + |\mathbf{g}_{EAP,p}^H \mathbf{v}_p^*|) \exp\{j\angle(\mathbf{g}_{EAP,p}^H \mathbf{v}_p^*)\} \\ &= |\mathbf{g}_{sp}^H \mathbf{w}_p^*| + |\mathbf{g}_{EAP,p}^H \mathbf{v}_p^*| \\ &\stackrel{(a)}{>} |\mathbf{g}_{sp}^H \mathbf{w}_p^* + \mathbf{g}_{EAP,p}^H \mathbf{v}_p^*| \\ &\geq \sqrt{t^*(\mathbf{g}_{sp}^H \mathbf{Q}_s^* \mathbf{g}_{sp} + \sigma_{PR}^2)}, \end{aligned} \quad (53)$$

where “ $\geq$ ” in (a) holds strictly, as a result of  $\angle(\mathbf{g}_{sp}^H \mathbf{w}_p^*) \neq \angle(\mathbf{g}_{EAP,p}^H \mathbf{v}_p^*)$ . According to (53), it holds true that  $\exists \mathbf{w}_p'' = \delta \mathbf{w}_p'$ , where  $\delta \in [0, 1)$ , such that

$$\begin{aligned} |\mathbf{g}_{sp}^H \mathbf{w}_p' + \mathbf{g}_{EAP,p}^H \mathbf{v}_p^*| &> |\mathbf{g}_{sp}^H \mathbf{w}_p'' + \mathbf{g}_{EAP,p}^H \mathbf{v}_p^*| = \delta |\mathbf{g}_{sp}^H \mathbf{w}_p^*| + |\mathbf{g}_{EAP,p}^H \mathbf{v}_p^*| \\ &> t^*(\mathbf{g}_{sp}^H \mathbf{Q}_s^* \mathbf{g}_{sp} + \sigma_{PR}^2). \end{aligned} \quad (54)$$

Meanwhile, we change the solution of  $\varrho^*$  to be  $\varrho'$  which is expressed as

$$\varrho' = \frac{\text{Tr}(\mathbf{Q}_s^*) + \delta^2 \|\mathbf{w}_p^*\|^2}{\text{Tr}(\mathbf{Q}_s^*) + \|\mathbf{w}_p^*\|^2} \varrho^* < \varrho^*. \quad (55)$$

So far, by changing the solution from  $\varrho^*$  to  $\varrho'$ , it is observed that the constraints (18b) and (18c) still hold, for the fact that the LHS of (18b) is a monotonically decreasing function over  $\varrho \in [0, 1]$ . Then we take the next step of changing  $t^*$  to  $t'$  as follows.

$$t' = \min \left\{ (1 - \varrho') P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{-1}(\varrho', \mathbf{X}^*) \mathbf{h}_{p,ST}, \frac{|\mathbf{g}_{sp}^H \mathbf{w}_p'' + \mathbf{g}_{EAP,p}^H \mathbf{v}_p^*|^2}{\mathbf{g}_{sp}^H \mathbf{Q}_s^* \mathbf{g}_{sp} + \sigma_{PR}^2} \right\} > t^*. \quad (56)$$

Consequently, by changing the solution of  $\mathbf{w}_p^*$ ,  $\varrho^*$  and  $t^*$  to  $\mathbf{w}_p''$ ,  $\varrho'$ , and  $t'$  without changing others, we find that a larger objective value to (P1.1) is achieved without violating any other constraints, due to the increasing  $\log_2(1 + t')$ . This nevertheless contradicts to the claimed optimality achieved by  $t^*$ . Hence, the proof is complete.

## APPENDIX C

### PROOF OF PROPOSITION 4.1

Algorithm 1 will generate a sequence of feasible points  $\{\mathbf{X}^{(n)}, \mathbf{Q}_s^{(n)}, \mathbf{w}_p^{(n)}, \mathbf{v}_p^{(n)}, t^{(n)}\}$  to problem (P1.1-1), since for each iteration the feasible region to (P1.1-1') is always a subset of that to (P1.1-1). For the  $n$ th iteration,  $\{\bar{\mathbf{X}}^{(n)}, \bar{\mathbf{Q}}_s^{(n)}, \bar{\mathbf{w}}_p^{(n)}, \bar{\mathbf{v}}_p^{(n)}, \bar{t}^{(n)}\}$  is chosen as a feasible solution to (P1.1-1'), while  $\{\mathbf{X}^{(n+1)}, \mathbf{Q}_s^{(n+1)}, \mathbf{w}_p^{(n+1)}, \mathbf{v}_p^{(n+1)}, t^{(n+1)}\}$  is the returned optimal solution to (P1.1-1'). Hence, denoting the objective function of (P1.1-1') as  $h_1$  with its (implicit) dependence on the optimization variables omitted,  $h_1^{(n+1)} \geq h_1(\bar{\mathbf{X}}^{(n)}, \bar{\mathbf{Q}}_s^{(n)}, \bar{\mathbf{w}}_p^{(n)}, \bar{\mathbf{v}}_p^{(n)}, \bar{t}^{(n)}) = h_1^{(n)}$ . As a result, we arrive at a non-decreasing sequence  $\{h_1^{(n)}\}$ .

Furthermore, we show that the solutions generated by the sequence  $\{\mathbf{X}^{(n)}, \mathbf{Q}_s^{(n)}, \mathbf{w}_p^{(n)}, \mathbf{v}_p^{(n)}, t^{(n)}\}$  are bounded. In fact, the boundedness for  $\mathbf{X}^{(n)}$  and  $\mathbf{v}_p^{(n)}$  can be justified via constraints (17a) and (17b), respectively. Consequently, it holds true that the nuclear norm of  $\mathbf{Q}_s^{(n)}$  and the  $\ell^2$ -norm of  $\mathbf{w}_p^{(n)}$ , which are bounded by  $\eta\varrho P_{\text{EH}}(\mathbf{X}^{(n)})$ , is also bounded from the above. As for  $t^{(n)}$ , according to (20c), it implies that

$$\begin{aligned} t^{(n)} &\leq (1 - \bar{\varrho}) P_p \mathbf{h}_{p,ST}^H \mathbf{A}^{(n)-1} \mathbf{h}_{p,ST} \\ &\leq (1 - \bar{\varrho}) P_p \lambda_{\max}(\mathbf{A}^{(n)-1}) \|\mathbf{h}_{p,ST}\|^2 \\ &\leq (1 - \bar{\varrho}) P_p \|\mathbf{h}_{p,ST}\|^2 / (1 - \bar{\varrho}) \sigma_{n_a}^2 + \sigma_{n_c}^2 \end{aligned} \quad (57)$$

where  $\lambda(\cdot)$  denotes the eigenvalue of the associated matrix.

Owing to the continuity of  $h_1$ , it follows that  $\{h_1^{(n)}\}$  is also bounded from the above. Hence, the non-decreasing sequence  $\{h_1^{(n)}\}$  is convergent to a real number denoted by  $h_1^*$ . Furthermore, according to Bolzano-Weierstrass theorem, the bounded sequence  $\{\mathbf{X}^{(n)}, \mathbf{Q}_s^{(n)}, \mathbf{w}_p^{(n)}, \mathbf{v}_p^{(n)}, t^{(n)}\}$  has at least one convergent subsequence, the accumulation point of which is denoted by  $\{\mathbf{X}^*, \mathbf{Q}_s^*, \mathbf{w}_p^*, \mathbf{v}_p^*, t^*\}$ . Therefore, we automatically arrive at  $h_1(\mathbf{X}^*, \mathbf{Q}_s^*, \mathbf{w}_p^*, \mathbf{v}_p^*, t^*) = h_1^*$ . A KKT point of problem (P1.1-1), namely,  $\{\mathbf{X}^*, \mathbf{Q}_s^*, \mathbf{w}_p^*, \mathbf{v}_p^*, t^*\}$  is thus obtained [28, Theorem 1].

A similar proof can be applied to problem (P1.2-1) and is thus omitted here for brevity.

## REFERENCES

- [1] FCC, "Spectrum policy task force," Federal Communications Commission, ET Docket No. 02-135, Tech. Rep., Nov. 2002.
- [2] J. Mitola and G. Q. Maguire, "Cognitive radio: Making software radios more personal," *IEEE Pers. Commun.*, vol. 6, no. 6, pp. 13–18, Aug. 1999.
- [3] X. Kang, Y.-C. Liang, A. Nallanathan, H. K. Garg, and R. Zhang, "Optimal power allocation for fading channels in cognitive radio networks: Ergodic capacity and outage capacity," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 940–950, Feb. 2009.
- [4] J. Xu and R. Zhang, "Comp meets smart grid: A new communication and energy cooperation paradigm," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 6, pp. 2476–2488, Jun. 2015.
- [5] S. Bi, Y. Zeng, and R. Zhang, "Wireless powered communication networks: an overview," *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 10–18, Apr. 2016.
- [6] S. Lee, R. Zhang, and K. Huang, "Opportunistic wireless energy harvesting in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 9, pp. 4788–4799, Sept. 2013.
- [7] G. Zheng, Z. Ho, E. A. Jorswieck, and B. Ottersten, "Information and energy cooperation in cognitive radio networks," *IEEE Trans. Signal Process.*, vol. 62, no. 9, pp. 2290–2303, May 2014.
- [8] S. Lee and R. Zhang, "Cognitive wireless powered network: Spectrum sharing models and throughput maximization," *IEEE Trans. Cogn. Commun. Netw.*, vol. 1, no. 3, pp. 335–346, Sept. 2015.
- [9] C. Zhai, J. Liu, and L. Zheng, "Cooperative spectrum sharing with wireless energy harvesting in cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5303–5316, Jul. 2016.
- [10] H. Ju and R. Zhang, "Optimal resource allocation in full-duplex wireless-powered communication network," *IEEE Trans. Commun.*, vol. 62, no. 10, pp. 3528–3540, Oct. 2014.
- [11] C. Zhong, H. A. Suraweera, G. Zheng, I. Krikidis, and Z. Zhang, "Wireless information and power transfer with full duplex relaying," *IEEE Trans. Commun.*, vol. 62, no. 10, pp. 3447–3461, Oct. 2014.
- [12] Y. Zeng and R. Zhang, "Full-duplex wireless-powered relay with self-energy recycling," *IEEE Wireless Commun. Lett.*, vol. 4, no. 2, pp. 201–204, Apr. 2015.
- [13] G. Zheng, I. Krikidis, and B. Ottersten, "Full-duplex cooperative cognitive radio with transmit imperfections," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2498–2511, May 2013.
- [14] X. Kang, C. K. Ho, and S. Sun, "Full-duplex wireless-powered communication network with energy causality," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5539–5551, Oct. 2015.
- [15] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1637–1652, Sept. 2014.
- [16] H. Xing, X. Kang, K.-K. Wong, and A. Nallanathan, "Optimization for DF relaying cognitive radio networks with multiple energy access points," in *to appear in Proc. IEEE Global Communications Conference (GLOBECOM)*, Washington, DC, USA, Dec. 2016.
- [17] X. Zhou, R. Zhang, and C. Ho, "Wireless information and power transfer: architecture design and rate-energy tradeoff," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4757–4767, Nov. 2013.
- [18] T. M. Kim, H. J. Yang, and A. J. Paulraj, "Distributed sum-rate optimization for full-duplex MIMO system under limited dynamic range," *IEEE Signal Process. Lett.*, vol. 20, no. 6, pp. 555–558, Jun. 2013.
- [19] B. P. Day, A. R. Margetts, D. W. Bliss, and P. Schniter, "Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range," *IEEE Trans. Signal Process.*, vol. 60, no. 7, pp. 3702–3713, Jul. 2012.
- [20] A. L. Yuille and A. Rangarajan, "The concave-convex procedure," *Neural Comput.*, vol. 15, no. 4, pp. 915–936, Apr. 2003.

- [21] H. H. Kha, H. D. Tuan, and H. H. Nguyen, "Fast global optimal power allocation in wireless networks by local D.C. programming," *IEEE Trans. Wireless Commun.*, vol. 11, no. 2, pp. 510–515, Feb. 2012.
- [22] M. Grant and S. Boyd, "CVX: Matlab software for disciplined convex programming, version 2.1," <http://cvxr.com/cvx>, Jun. 2015.
- [23] R. Zhang, "Cooperative multi-cell block diagonalization with per-base-station power constraints," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 9, pp. 1435–1445, Dec. 2010.
- [24] H. Xing, K.-K. Wong, A. Nallanathan, and R. Zhang, "Wireless powered cooperative jamming for secrecy multi-AF relaying networks," 2015, available online at arXiv:1511.03705.
- [25] A. A. Nasir, D. T. Ngo, X. Zhou, R. A. Kennedy, and S. Durrani, "Joint resource optimization for multicell networks with wireless energy harvesting relays," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6168–6183, Aug. 2016.
- [26] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge Univ. Press, 2004.
- [27] R. A. Horn and C. R. Johnson, *Matrix analysis*. Cambridge uni. press, 2012.
- [28] B. R. Marks and G. P. Wright, "Technical note a general inner approximation algorithm for nonconvex mathematical programs," *Oper. Res.*, vol. 26, no. 4, pp. 681–683, 1978.